SLEA: A Novel Scheme for Routing in Overlay IP/WDM Networks

Tong Ye, Yikai Su, *Member, IEEE*, Keyao Zhu, Lufeng Leng, *Member, IEEE*, Qingji Zeng, and Yaohui Jin

***Abstract*—This paper studies the routing problems in Internet protocol/wavelength-division-multiplexing (IP/WDM) networks based on the overlay routing algorithm (ORA) and the integrated routing algorithm (IRA), respectively. Although IRA usually outperforms ORA in terms of blocking performance, IRA exhibits disadvantages in control information exchange, network privacy issue, and wavelength port efficiency. In this paper, a new mechanism called the short lightpath establishment approach (SLEA) is proposed for ORA in order to tackle the problems in IRA and achieve similar (or even better) network performance at the same time. The main idea of SLEA is to ensure that each new lightpath created by ORA is restricted by an optical hop constraint when a subwavelength-granularity connection is routed in the optical layer. It follows that SLEA essentially avoids per-connection-based greedy treatment and improves network wide resource utilization by eliminating inefficient long optical bypasses. To implement SLEA in ORA, the Dijsktra's algorithm has been modified based on an extended layered graph model. SLEA does not introduce any additional signaling and computational complexity. The analysis and simulation in this paper show that there exists an optimal optical hop constraint for each particular network configuration such that SLEA-based ORA (SLEA-ORA) can efficiently utilize the network resource of concern. As a result, with the optimal optical hop constraint, SLEA-ORA could outperform ORA and IRA in terms of the bandwidth-blocking ratio (BBR) and the average number of IP hops of label-switched paths (LSPs).**

***Index Terms*—Integrated routing, Internet protocol (IP) hop, Internet protocol/wavelength-division-multiplexing (IP/WDM), lightpath, optical hop, overlay routing.**

I. INTRODUCTION

WAVELENGTH-DIVISION multiplexing (WDM) optical networks have emerged to meet the ever-growing traffic demand. It is widely believed that Internet protocol (IP)-based WDM optical networks, known as optical Internet, will be a major component of the next-generation Internet (NGI). Meanwhile, the technologies and ongoing standardization activities on multiprotocol label switching (MPLS) [1] and Generalized MPLS (GMPLS) [2] make the architecture of IP-over-WDM (IP/WDM) networks [3]–[11] feasible.

In IP/WDM networks, high-speed IP routers are connected to their peers through an optical layer network, which is composed of optical cross connects (OXCs) interconnected by WDM optical links. An OXC typically consists of multiple-wavelength switching fabrics, which optically process the traffic at the wavelength granularity. Through the configuration of OXCs, the optical layer can provide dynamic point-to-point logical connectivity between the IP routers in the form of coarse-grained lightpaths. A lightpath may span several optical links, and the number of optical links spanned by a lightpath is termed as its optical hops. In such a network, IP routers could support MPLS functions and thus are referred to as label-switched routers (LSRs). An LSR is attached to the OXC and switches or grooms [12]–[14] fine-grained label-switched paths (LSPs) over the lightpaths through the wavelength ports comprising optical transmitters (Txs) and optical receivers (Rxs). The number of lightpaths traversed by an LSP is referred to as its IP hops. Typically, the granularity of an LSP is much smaller than that of a wavelength, and a lightpath can provide service for a number of LSPs. Once a lightpath is no longer used by any LSP, it will be torn down immediately.

According to the interconnection styles between the IP layer and the optical layer, there are two categories for the IP/WDM networks: overlay model and integrated model [4]–[7], [15]. In the overlay model, the network routing, topology (i.e., link state) information distribution, and signaling protocols in the optical layer are independent of those in the IP layer. The resources used by the optical layer include fibers and wavelengths, which are not exposed to the LSRs. The set of lightpaths in the optical layer essentially defines a logical layer for the LSRs, and each LSR only keeps the information about such a topology. For an LSP request, an overlay routing algorithm (ORA) [6], [16] first computes a path in the logical layer. If this step fails, the request is then transferred to the optical layer through the user–network interface (UNI) [17] to set up a new lightpath through the routing and wavelength assignment (RWA) [18]–[21] algorithms. On the other hand, in the integrated model, a unified control plane is maintained. The topology perceived by each node (the LSR and the OXC) is an integrated IP/WDM topology, which includes the wavelength utilization of the optical links as well as the bandwidth usage of the lightpaths. Through an integrated routing algorithm (IRA) [7], [22], the LSR can compute the complete path to another

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LSR in one step, considering the optical links and the existing lightpaths jointly.

Previous results [15] show that IRA tends to outperform ORA in terms of blocking performance, especially when the wavelength ports are sufficient. One explanation is that ORA computes a path separately in either the logical layer or the optical layer while IRA considers the integrated IP/WDM topology. When ORA fails to find a path in either layer, IRA may satisfy the request by allocating a path traversing both the existing lightpaths and the optical links. Also, IRA can optimally utilize the wavelength resources across the integrated network topology through some routing strategies [7], [22] while ORA can only provide optimal performance in either layer separately.

However, IRA has several significant disadvantages. First, a large number of control messages have to be frequently exchanged across the network, since in the integrated model each node should have the complete information of the network topology. Second, in practice, separate management for each network layer may be preferred to keep the network information from other layers [e.g., virtual private network (VPN) [23]]. Third, IRA is not able to utilize the wavelength ports efficiently. To satisfy a request, IRA may set up excessive new lightpaths as long as there are available ports in the nodes, which results in nonoptimized utilization of ports. On the other hand, in the overlay model, the information exchange can be reduced significantly, the privacy of each layer can be easily ensured, and ORA always first tries to route the traffic in the logical layer to save the number of ports. Therefore, ORA may be more attractive than IRA if a mechanism can be developed to improve its blocking performance. This paper thus proposes an approach called the short lightpath establishment approach (SLEA), which can serve as such a mechanism.

Due to the characteristics of the overlay model, ORA always considers the logical layer and the optical layer separately in path selection. After ORA fails to find a path in the logical layer, it tends to set up a new lightpath with possibly a large number of optical hops, especially when there exist many nodes between the source and the destination. Although the optical bypass function is introduced to alleviate the electronic bottleneck and to reduce the utilization of wavelength ports [5], [12], excessive establishment of long lightpaths may result in a low wavelength resource efficiency (W-Eff). The lightpath can only be used to transport the traffic between its end nodes since it optically bypasses all intermediate nodes. Meanwhile, the total traffic that the lightpath can carry is constrained by the wavelength capacity (e.g., OC-192), no matter how many optical links it spans. To handle a single LSP request, it may be optimal for ORA to establish a long lightpath. However, over a longer duration when multiple requests arrive, the connections through long lightpaths set up by the ORA may not be optimal anymore. Therefore, it is necessary to avoid per-connection-based greedy treatment and to improve networkwide resource utilization by eliminating inefficient long optical bypasses in ORA. This is achieved through the proposed SLEA, which ensures that each new lightpath created by ORA is constrained by a given optical hop constraint when a subwavelength-granularity connection is routed in the optical layer. Our analysis and simulation show that there exists an optimal value for the optical hop constraint for each particular network configuration such that SLEA-based ORA (SLEA-ORA) can efficiently utilize the network resource of concern. Consequently, with the optimal optical hop constraint, SLEA can improve the performance of ORA significantly, and SLEA-ORA can even outperform IRA in terms of bandwidth-blocking ratio (BBR) and the average number of IP hops of LSPs.

The rest of the paper is organized as follows. In Section II, we describe the system model and provide some definitions. In Section III, we propose the SLEA scheme, and a qualitative analysis is presented to show that SLEA can perform well with ORA. To implement SLEA in ORA, Dijkstra's algorithm [24] is modified based on a layered graph model in Section IV. Simulation results and discussions are presented in Section V. Finally, Section VI concludes this paper.

II. System Model and Definition

An IP/WDM network can be modeled by a graph $G(N, E)$, where N is the node set and E is the set of bidirectional optical links. For any link $e_{ij} \in E$, there are F optical fibers, each of which contains W wavelengths. We assume that the wavelength sets in all fibers are the same, i.e., $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$. Therefore, there are $F \times W$ wavelength channels in either direction of each optical link. In this paper, a wavelength channel corresponds to the use of a wavelength in one fiber interconnecting two adjacent nodes. A lightpath spanning l optical links consumes l wavelength channels.

In IP/WDM networks, each node is an OXC controlled by an LSR, and the OXC has no wavelength conversion [25] capability. Therefore, a lightpath has to be established with the same wavelength on all the optical links along its route, which is known as wavelength continuity constraint. Note that the effect of SLEA on ORA is almost independent of the presence of wavelength conversion. The traffic is assumed to be uniformly distributed among all the node pairs. LSP requests arrive at the network according to an independent Poisson process with a mean arrival rate of λ, and the LSP holding time is exponentially distributed with a mean value of $1/\mu$. $\mathcal{R}(s, d, b)$ is used to represent a request, where s is the ingress router, d is the egress router, and b is the bandwidth requirement assumed to be routed without traffic splitting. Let B be the full wavelength bandwidth and $\overline{b}$ be the average value of bs, and in practice $0 < b \leq B$ and $\overline{b} \ll B$. We use $\eta = \overline{b}/B$ to denote a request's average bandwidth normalized to B. The value of $\rho = \eta\lambda/\mu$ corresponds to the network offered load.

The major objective of the algorithms in this paper is to minimize the BBR and to achieve a small average number of IP hops of LSPs. In an IP/WDM network, the wavelengths and ports are limited resources. A good blocking performance could be obtained if an algorithm can utilize the resources efficiently. Therefore, we also consider W-Eff and port-resource efficiency (P-Eff) as two important performance measures. To define them, let $\mathcal{B}(t)$ be the total bandwidth of all the LSPs being carried at time t, $\mathcal{W}(t)$ be the total number of wavelength channels that are used, and $\mathcal{P}(t)$ be the total number of Txs (or Rxs) that are busy. Then, W-Eff at time t is defined as $\mathcal{U}_w(t) \stackrel{\text{def}}{=} \mathcal{B}(t)/(\mathcal{W}(t) \times B)$, and accordingly P-Eff is defined as $\mathcal{U}_p(t) \stackrel{\text{def}}{=} \mathcal{B}(t)/(\mathcal{P}(t) \times B)$. The time-average W-Eff and P-Eff are given as

$$\mathcal{U}_w \stackrel{\text{def}}{=} \lim_{T\to\infty} \frac{1}{T} \int_0^T \mathcal{U}_w(t)\mathrm{d}t$$

and

$$\mathcal{U}_p \stackrel{\text{def}}{=} \lim_{T\to\infty} \frac{1}{T} \int_0^T \mathcal{U}_p(t)\mathrm{d}t.$$

III. Proposed Scheme and Analysis

To solve the problems associated with ORA as described in Section I, we propose an approach called SLEA to improve the performance of ORA in Section III-A. Then, in Section III-B, we carry out a qualitative analysis to show that there is an optimal optical hop constraint to achieve a maximal P-Eff for SLEA-ORA.

A. Proposed Scheme: SLEA-Based ORA (SLEA-ORA)

SLEA-ORA allows us to create multiple new lightpaths for a request. For a request $\mathcal{R}$, after SLEA-ORA fails to find a path in the logical layer, it does the following.

- Case 1) If $b < B$, the lightpath establishment should be subject to an optical hop constraint, i.e., no new lightpath should be longer than the limit set by the optical hop constraint. By doing so, SLEA-ORA prevents from creating excessive long lightpaths in this case.
- Case 2) If $b = B$, no constraint should be applied, i.e., a single lightpath is set up for $\mathcal{R}$. In this case, the bandwidth on the created lightpath is completely occupied by $\mathcal{R}$, and it cannot provide service for the subsequent LSPs. Obviously, if more than one lightpath is set up for $\mathcal{R}$ when $b = B$, P-Eff will be lower.

The optical hop constraint is an integer number given beforehand, which is denoted by $\mathcal{C}$. When $\mathcal{C} = \infty$, SLEA-ORA is similar but not equal to ORA, because SLEA-ORA is allowed to create multiple lightpaths for $\mathcal{R}$ with $b < B$ if necessary while ORA only sets up a single lightpath.

B. Analysis: P-Eff of SLEA-ORA

It is obvious that W-Eff will increase with decreasing $\mathcal{C}$. However, the dependence of P-Eff on $\mathcal{C}$ remains unclear. In this part, we provide a qualitative analysis to investigate the relationship between P-Eff and $\mathcal{C}$. To facilitate the presentation, we consider a unidirected ring network, which is a typical topology and has been studied extensively.

Let us consider a unidirectional ring network in Fig. 1(a), in which there are $2h$ nodes and $2h$ optical links. At time t_0, two LSP requests arrive at the network, i.e., $\mathcal{R}_1(v_0, v_h, b_1)$ and $\mathcal{R}_2(v_h, v_0, b_2)$, where $b_1 < B$ and $b_2 < B$. It is assumed that initially there is no lightpath available and ORA has to create new lightpaths for $\mathcal{R}_1$ and $\mathcal{R}_2$. In this case, for each request, ORA consumes a pair of ports and h wavelength channels to set up a lightpath, while SLEA-ORA establishes $x/2 \approx h/\mathcal{C}$ lightpaths using $x/2$ pairs of ports and h wavelength channels. It is clear that $x \propto 1/\mathcal{C}$.

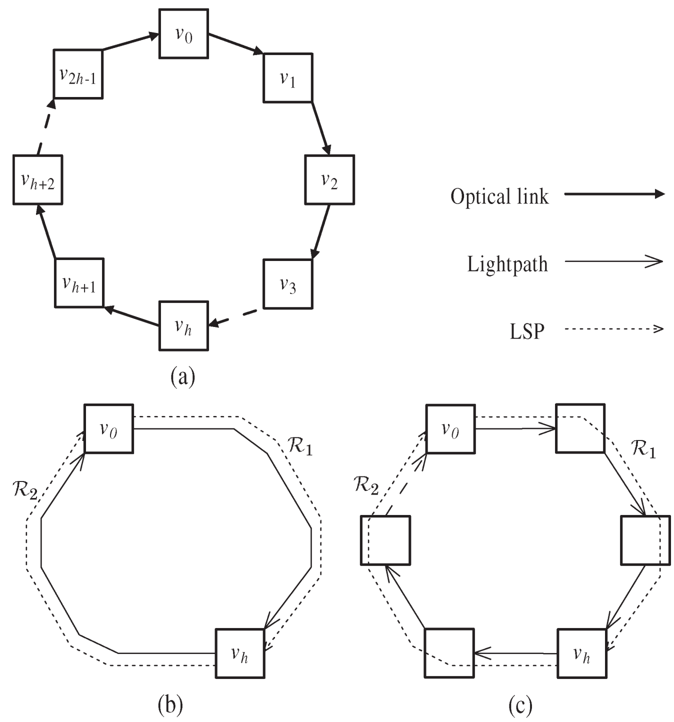

Fig. 1. Illustration of two lightpath establishment approaches. (a) A unidirected ring network. A request arrives for a connection from v_0 to v_h while another one from v_h to v_0. (b) ORA: Establish two lightpaths for two requests. (c) SLEA-ORA: Establish x lightpaths for each request.

We analyze the case where the offered load in the network (i.e., ρ) is not very low. Without loss of generality, we assume that, in the short time interval of $(t_0, t_0 + \Delta t)$, M $(M > 0)$ requests arrive at the network for each node pair and no request departs from the network. A large M indicates that ρ is large. In order to save the ports and wavelength channels for future requests, ORA and SLEA-ORA prefer routing each request in the logical layer first because creating new lightpaths will consume additional ports and wavelength channels. Hence, we would investigate how much bandwidth the x lightpaths created by SLEA-ORA can carry in the case where no new lightpath is created in Δt.

According to the above description, x nodes connected by lightpaths form $x(x-1)$ node pairs in Δt and request a total of $x(x-1)M\bar{b}$ units of bandwidth demands to the lightpaths. The bandwidth demands offered to each lightpath are computed as

$$M \times \bar{b} \times \sum_{i=1}^{x} (i-1) = \frac{x(x-1)M\bar{b}}{2}.$$

This indicates that each lightpath will carry half of the total traffic generated by the node pairs. An example is shown in

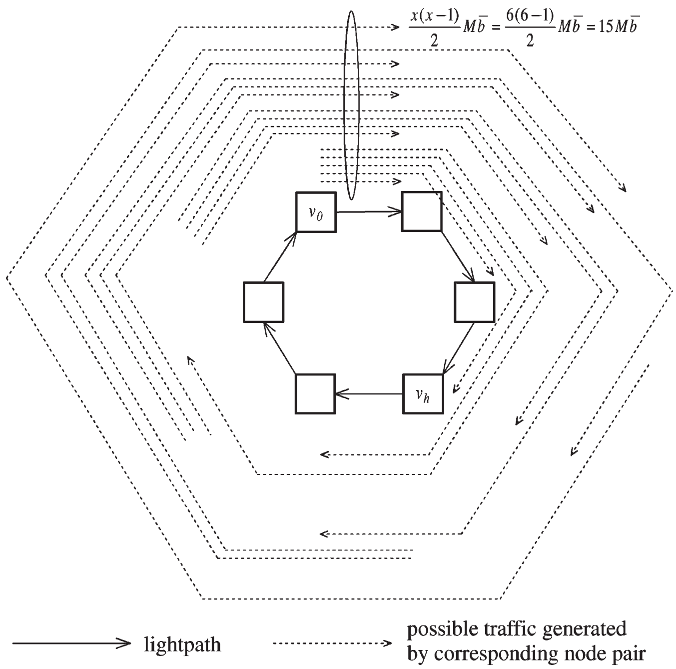

Fig. 2. Example: SLEA-ORA sets up six lightpaths for two requests. The traffic generated by 15 node pairs possibly passes through each lightpath.

Fig. 2. There are six lightpaths in the network. 30 node pairs offer $30M\bar{b}$ units of bandwidth demands to the lightpaths and $15M\bar{b}$ units for each lightpath. However, all the traffic offered to a lightpath may not be satisfied because the total bandwidth of a lightpath is bounded by B. As a result, a lightpath can carry a maximum traffic of

$$\min\left\{B, \frac{x(x-1)M\bar{b}}{2}\right\}.$$

If we set $x(x-1)M\bar{b}/2 = B$, a critical x, denoted as x_c, can then be computed as

$$x_c = \frac{1}{2}\left(1+\sqrt{1+\frac{8}{M\eta}}\right).$$

When $x \le x_c$, the lightpaths can carry all the traffic offered to them, i.e., $\mathcal{B}(\Delta t) = x(x-1)M\bar{b}$. In this case, the $\mathcal{U}_p(\Delta t)$ of SLEA-ORA is derived as

$$\mathcal{U}_p(\Delta t) = M\eta(x-1)$$

where $\mathcal{U}_p(\Delta t) \propto x$ or $\mathcal{U}_p(\Delta t) \propto 1/\mathcal{C}$.

When $x > x_c$, each lightpath can carry at most $B/\bar{b}$ LSPs. Therefore, x lightpaths carry a total of $2B/\bar{b}$ LSPs and $2B$ units of bandwidth demands. The $\mathcal{U}_p(\Delta t)$ of SLEA-ORA is then given as

$$\mathcal{U}_p(\Delta t) = \frac{2}{x} \propto \mathcal{C}.$$

It is clear that $\mathcal{U}_p(\Delta t)$ increases with $\mathcal{C}$. Therefore, with respect to P-Eff, there exists an optimal $\mathcal{C} \approx h/x_c < \infty$ called $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$, and SLEA-ORA ($\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$) has the highest P-Eff, as shown in Fig. 3.

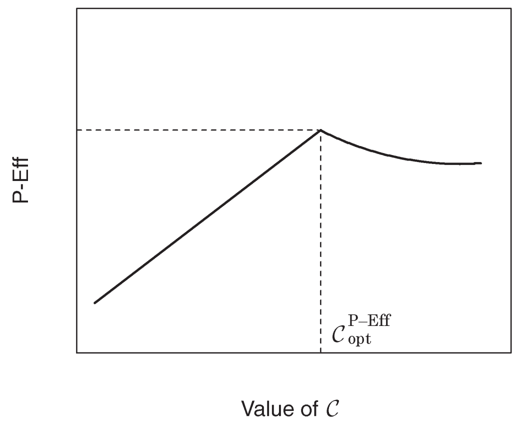

Fig. 3. Illustration of the optimal $\mathcal{C}$. There is an optimal value for $\mathcal{C}$ denoted as $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$. P-Eff first increases with $\mathcal{C}$ when $\mathcal{C} \le \mathcal{C}_{\text{opt}}^{\text{P-Eff}}$ and then decreases with the increase of $\mathcal{C}$ when $\mathcal{C} > \mathcal{C}_{\text{opt}}^{\text{P-Eff}}$.

The qualitative analysis shows that the value of $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$ increases with η and M, indicating that $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$ increases with the average granularity of the LSPs and the offered load. An extreme case is that when $\eta = 1$, no optical hop constraint should not be used, as in Case 2) mentioned in Section III-A. Also, the fact that $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$ increases with the offered load consists with the simulation results presented in Section V.

However, our model cannot be used to analyze the case where the offered load is very low (e.g., $M = 0$). In this case, the arrival rate of the requests is so low that no request arrives before the departure of the previous one. As a result, there is no bandwidth multiplexing, and the lightpaths only provide service for one request. Therefore, SLEA-ORA has a lower $\mathcal{U}_p(\Delta t)$ than ORA under the low-arrival condition.

IV. Implementation of SLEA in ORA

In implementing SLEA-ORA, the challenge is to find a path in the optical layer subject to an optical hop constraint that cannot be achieved through the classical shortest path algorithm. In this section, Dijkstra's algorithm is modified to solve this problem based on a layered graph model [20], [21].

A. Extended Layered Graph Model

In an overlay IP/WDM network $G(N,E)$, an OXC maintains the topology including the information about utilization of fibers, wavelengths, and wavelength ports equipped in each node. In this section, we construct a layered graph for such a topology, which can be defined as $G_L(N_L, E_L)$.

In $G_L(N_L, E_L)$, each OXC in $i \in N$ is replicated $2 \times W$ times. These vertices are denoted by $n_i^E(1), n_i^S(1), n_i^E(2), n_i^S(2), \ldots, n_i^E(W), n_i^S(W) \in N_L$, respectively. For all $1 \le w \le W$, we use a directed edge denoted as $l_{ii}(w)$ to connect $n_i^E(w)$ to $n_i^S(w)$. This edge is introduced to enable the optical hop control of newly established lightpaths and thus called an optical hop control link. If there is $e_{ij} \in E$, for all $1 \le w \le W$, we connect $n_i^S(w)$ to $n_j^E(w)$ using a directed edge, which is referred to as a wavelength link and denoted as $l_{ij}(w)$. $l_{ij}(w)$ carries F equivalent wavelength channels. If

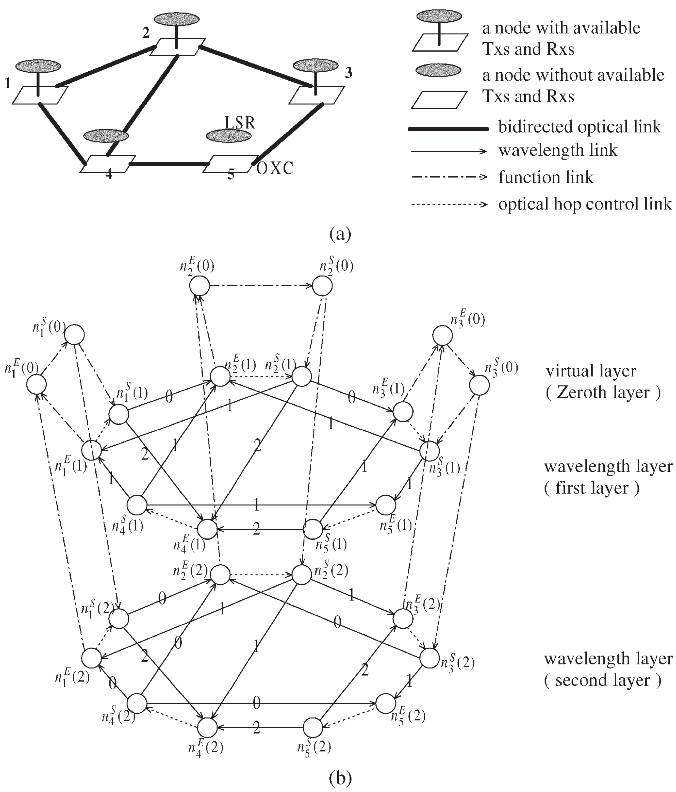

Fig. 4. Illustration for the layered graph model. In the network, each node is an OXC controlled by an LSR. Nodes 1, 2, and 3 have available wavelength ports. Each optical link is bidirectional. On each direction of an optical link, there are $F = 2$ optical fibers, and the wavelength set of each fiber is $\Lambda = \{\lambda_1, \lambda_2\}$. (a) Physical IP/WDM network. (b) Layered graph for the optical layer.

there are available ports in $i \in N$, we introduce two new vertices $n_i^E(0)$, $n_i^S(0)$ to G_L. Then, via the edges called function links, $n_i^E(0)$ is connected to $n_i^S(0)$, $n_i^E(w)$s are connected to $n_i^E(0)$ if there are available Rxs, and $n_i^S(0)$s are connected to $n_i^S(w)$ with available Txs. We assume that the capacity on a function link is infinity and the cost of a function link is set to ε ($\varepsilon \to 0^+$). The subgraph formed by $n_i^E(w)$s and $n_i^S(w)$s in G_L is called the wth wavelength layer ($w \geq 1$), and the one constructed by $n_i^E(0)$s and $n_i^S(0)$s is termed as the virtual layer.

An illustration is provided in Fig. 4. Fig. 4(a) shows the physical topology of an IP/WDM network, in which the wavelength set is $\Lambda = \{\lambda_1, \lambda_2\}$ and $F = 2$. Fig. 4(b) is a plot showing the layered graph containing a virtual layer and two wavelength layers. The numbers labeled on the wavelength link stand for available channels. Since there are available ports in nodes 1, 2, and 3, we introduce $n_1^S(0)$, $n_1^E(0)$, $n_2^S(0)$, $n_2^E(0)$, $n_3^S(0)$, $n_3^E(0)$, and the corresponding function links.

The issues on how to maintain a layered graph of an IP/WDM network in a node and the associated complexity issue have been addressed in [26].

B. Issues on Path Selection

In this paper, the path selection algorithms are based on Dijkstra's algorithm. The assignment of link costs thus provides a path selection strategy. A good strategy can not only utilize the resource efficiently but also possess low complexity.

Several strategies have been proposed for the integrated IP/WDM networks, such as integrated min-hop (IMH) routing [22], maximum open capacity routing algorithm (MOCA) [22], and hop-based IRA (HIRA) [7]. MOCA always selects a route for the current LSP request so that the residual capacities between the source and destination are maximized. IMH tries to minimize the number of the entities (the lightpath and the optical links) used by each request and HIRA tends to select a route with the minimal number of optical hops. MOCA is much more complicated than IMH and HIRA because the maximum flow values for all the router pairs have to be computed in order to set cost for each link in MOCA. Recent results show that HIRA remarkably outperforms MOCA and IMH [15] in terms of blocking probability for LSP requests.

To compare ORA, SLEA-ORA, and IRA, we adopt the routing strategy of HIRA. The cost of a lightpath with sufficient residual capacity for the request is determined by its optical hops. In G_L, all the wavelength links with available channels have the same cost, i.e., one unit. Also, the costs of optical hop control links are initialized to zero. Note that, similar to HIRA, MOCA and IMH can be used in combination with ORA, IRA, and SLEA-ORA.

C. Modified Dijkstra's Algorithm for Optical Hop Constraint

Based on the layered graph model, routing $\mathcal{R}(s, d, b)$ in the optical layer is reduced to finding a route from $n_s^S(0)$ to $n_d^E(0)$ in G_L. However, if Dijkstra's algorithm is directly applied in G_L, it is difficult to find a path for a request in the optical layer when each lightpath to be set up is limited by the optical hop constraint.

This observation can be illustrated in the following example. In Fig. 4(b), we want to find the minimal cost path from $n_1^S(0)$ to $n_3^E(0)$ with an optical hop constraint of 2. By employing Dijkstra's algorithm, we find the path as $\widehat{p}_1 = \langle n_1^S(0), n_1^S(1), n_4^E(1), n_4^S(1), n_5^E(1), n_5^S(1), n_3^E(1), n_3^E(0)\rangle$. A three-hop lightpath is created consequently, which is longer than the constraint. However, we cannot simply split it into two parts because there is no available port in nodes 4 and 5.

Therefore, the classical Dijkstra's algorithm must be modified to achieve the objective. Our modified Dijkstra's algorithm maintains a set of vertices S whose final shortest path costs from the source have already been determined, and we define $\mathcal{H}(\cdot)$ as an optical hop counter for each vertex in the wavelength layers. The algorithm repeats the following steps: 1) select the vertex $u \in N \setminus S$ with the minimum shortest path estimate; 2) add u to S; 3) run an additional procedure as shown in Procedure 1; and 4) relax all the vertices, which are adjacent to u but not in S. Step 3 is added to the classical Dijkstra's algorithm to achieve our objective. Our key idea is to control the growth of the spanning tree in G_L by dynamically modifying the costs of the optical hop control links when Dijkstra's algorithm is running. Procedure 1 checks the type of the current vertex and its predecessor and determines the cost of optical hop control links according to such decision. It is obvious that this procedure almost does not introduce any additional complexity.

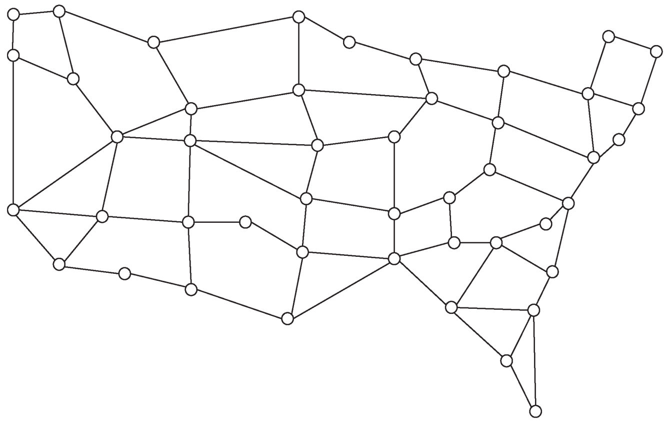

Fig. 5. Topology studied in our simulation: 46-node USNET.

Procedure 1 Modification (**Note**: w below stratifies $w > 0$.)

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if u corresponds to a vertex n_i^S(w) ∈ G_L, then
    let v be the predecessor of u
    if v corresponds to a vertex n_i^E(w), then
        H(u) ← H(v)
    else
        H(u) ← 0
    end if
else if u corresponds to a vertex n_i^E(w), then
    let v be the predecessor of u
    H(u) ← H(v) + 1
    if H(u) ≥ C, then
        set the cost of l_ii(w) to ∞
    end if
end if
```

Here, we explain how the modified Dijkstra's algorithm works using the above example. In the beginning, we initialize $S = \{n_1^S(0)\}$. Obviously, the first vertex added to S is $n_1^S(1)$. Since the predecessor of $n_1^S(1)$ is $n_1^S(0)$, $\mathcal{H}(n_1^S(0)) = 0$. Accordingly, a spanning tree of G_L is growing with the expansion of S. $n_4^E(1)$ is now the closest vertex; thus, $S = S \bigcup \{n_4^E(1)\}$. Since the predecessor of $n_4^E(1)$ is $n_1^S(1)$, its $\mathcal{H}(n_4^E(1)) = \mathcal{H}(n_1^S(1)) + 1 = 1 < \mathcal{C} = 2$. Subsequently, the algorithm then adds $n_4^S(1)$ into S, and $\mathcal{H}(n_4^S(1)) = \mathcal{H}(n_4^E(1)) = 1$. According to the computation based on the algorithm, $n_2^E(1)$ and $n_5^E(1)$ are considered as the successors of $n_4^S(1)$. Therefore, $\mathcal{H}(n_2^E(1)) = \mathcal{H}(n_4^S(1)) + 1 = 2 = \mathcal{C}$ and $\mathcal{H}(n_5^E(1)) = \mathcal{H}(n_4^S(1)) + 1 = 2 = \mathcal{C}$. At that point, the costs of $l_{22}(1)$ and $l_{55}(1)$ are set to ∞ through Procedure 1. Then, the growth of spanning tree is changed, and the path $\widehat{p}_1$ cannot be found due to this operation. As a result, we obtain the path as $\widehat{p}_2 = \langle n_1^S(0), n_1^S(1), n_4^E(1), n_4^S(1), n_2^E(1), n_2^E(0), n_2^S(0), n_2^S(2), n_3^E(2), n_3^E(0)\rangle$. This selection finally results in a two-hop lightpath and a one-hop lightpath. The two newly created lightpaths are $1 \xrightarrow{\lambda_1} 4 \xrightarrow{\lambda_1} 2$ and $2 \xrightarrow{\lambda_2} 3$ in the physical network, respectively.

V. Performance Evaluation

We perform simulations in a network environment based on the following assumptions: 1) the full wavelength bandwidth is OC-192; 2) the number of requests follows the distribution OC-1:OC-3:OC-12:OC-48:OC-192 = 320:20:12:6:1 (which is close to the bandwidth distribution in a practical backbone network [27]); 3) the number of ports at a node is set as the nodal degree times $F \times W$ times a scalar Δ $(0 \leq \Delta \leq 1)$; 4) the 46-node USNET [28] is studied as shown in Fig. 5; 5) both F and W are fixed to 4; 6) as mentioned in Section IV-B, the routing strategy of HIRA is adopted in ORA, SLEA-ORA, and IRA (i.e., HIRA). The performance metrics are W-Eff, P-Eff, BBR, and the average number of IP hops of LSPs.

A. Limited Number of Ports: SLEA-ORA Versus ORA Versus IRA

In a practical network, the number of ports equipped in a node might be low due to the associated cost. Therefore, we first compare different algorithms in Fig. 6 for $\Delta = 0.3$.

We investigate W-Eff versus the offered load (i.e., ρ) in Fig. 6(a). The SLEA-ORA(inf) in the figure means that the optical hop constraint in SLEA-ORA is set to infinity. The results show that the tighter the optical hop constraint is, the higher W-Eff can be achieved by SLEA-ORA. SLEA-ORA(inf) and ORA have almost the same W-Eff, which is lowest. SLEA-ORA(1) and SLEA-ORA(2) have a much higher W-Eff than SLEA-ORA(inf). Here, IRA has a slightly lower W-Eff than SLEA-ORA(3).

P-Eff versus ρ for different optical hop constraints is shown in Fig. 6(b). For a given integer m, SLEA-ORA(m) has the highest P-Eff (i.e., $\mathcal{C}_{\text{opt}}^{\text{P-Eff}} = m$) in a certain ρ interval. For example, $\mathcal{C}_{\text{opt}}^{\text{P-Eff}} = 3$ when $118 < \rho < 190$ Erlang, while $\mathcal{C}_{\text{opt}}^{\text{P-Eff}} = 4$ when $\rho > 190$ Erlang. This indicates that the value of $\mathcal{C}_{\text{opt}}^{\text{P-Eff}}$ increases with ρ, as we have discussed in Section III. The result also shows that, for a given ρ, P-Eff increases with $\mathcal{C}$ when $\mathcal{C} < \mathcal{C}_{\text{opt}}^{\text{P-Eff}}$; however, P-Eff decreases slowly with $\mathcal{C}$ when $\mathcal{C} > \mathcal{C}_{\text{opt}}^{\text{P-Eff}}$, which agrees with our analysis. SLEA-ORA(inf) almost has the same P-Eff as ORA. IRA shows a poor performance, and its P-Eff is even lower than that of SLEA-ORA(2). A mechanism that can achieve efficient port utilization for IRA has not been found up to now.

The BBR of SLEA-ORA(m) is related to its W-Eff and P-Eff together as shown in Fig. 6(c). SLEA-ORA(1) has the highest BBR. When $\mathcal{C} = 2$, BBR decreases significantly. SLEA-ORA(3) achieves the lowest BBR when $\rho < 280$ Erlang. While for $\mathcal{C} > 3$, BBR increases. SLEA-ORA(inf) slightly outperforms ORA. The observations prove that SLEA-ORA(3) is a good solution in terms of BBR for this topology when $\Delta = 0.3$. As shown in Fig. 6(a) and (b), the W-Eff of IRA is 5% higher than that of ORA, whereas ORA outperforms IRA in P-Eff by 5%. Overall, IRA demonstrates a better BBR than ORA due to the "integrated" characteristic of IRA. One interesting result in Fig. 6(c) is that SLEA-ORA(3) and SLEA-ORA(4) even clearly outperform IRA throughout the full range of ρ. The main reason is that SLEA-ORA(3) has the higher W-Eff and P-Eff than IRA. The P-Eff of SLEA-ORA(4) is 6.5% higher than that of IRA, while its W-Eff is only 1.5% lower than that of IRA. This indicates that, when the number of ports is small, the SLEA

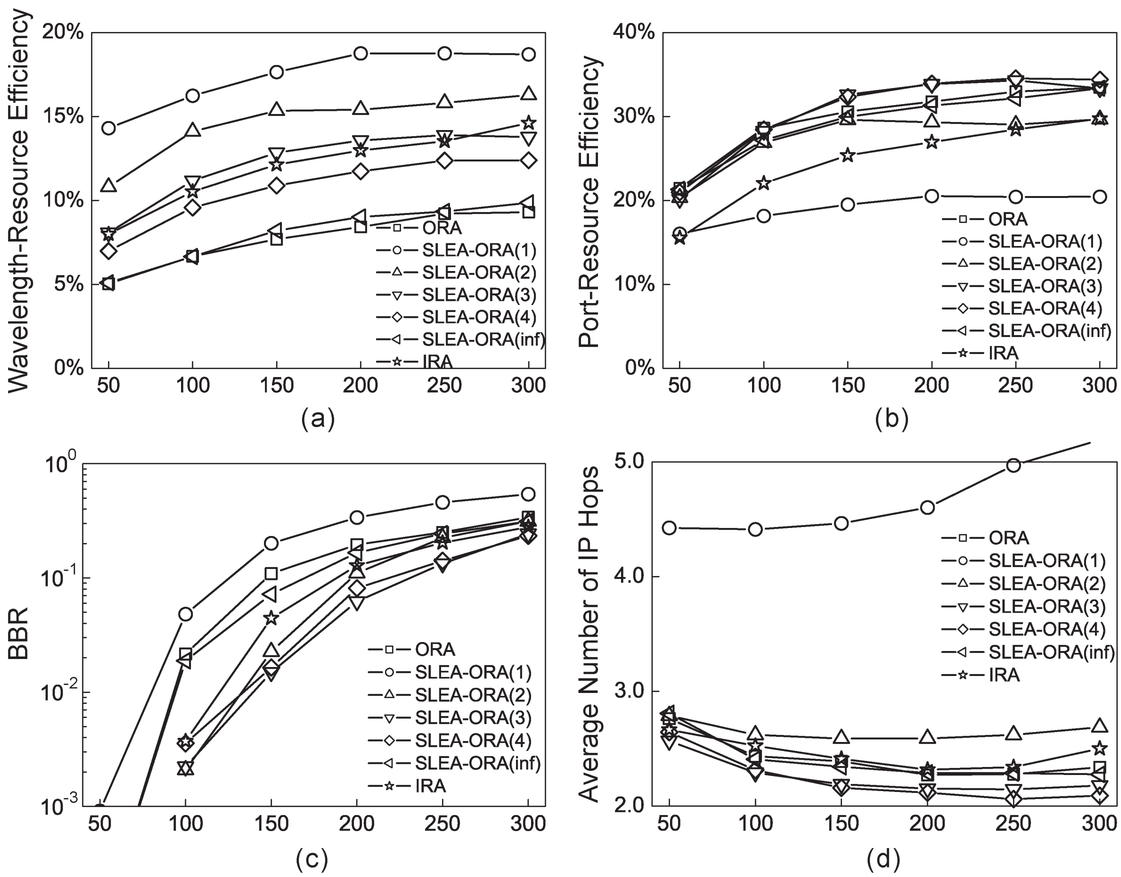

Fig. 6. Network performance versus network traffic load with $\Delta = 0.3$ for ORA, SLEA-ORA, and IRA. (a) W-Eff. (b) P-Eff. (c) BBR. (d) Average number of IP hops. "SLEA-ORA(inf)" means the optical hop constraint in SLEA-ORA is set to infinity.

with a carefully selected $\mathcal{C}$ could make ORA more desirable than IRA because SLEA-ORA not only requires much less information exchange but also has a better blocking performance than IRA.

In IP/WDM networks, latency is mainly induced by electronic processing. A connection linking more intermediate IP routers suffers a larger processing latency. Here, our motivation for comparing the average numbers of IP hops is to evaluate the latency performance of different schemes. We evaluate the average number of IP hops of LSPs in Fig. 6(d). SLEA-ORA(1) shows on average a much larger number of IP hops than the others because the network transports the traffic like an IP over point-to-point WDM network [5] as long as the LSP's bandwidth requirement is less than OC-192. When $\mathcal{C}$ increases to 2, this situation is greatly improved due to the bypass functions of the lightpaths. For this topology, the result shows that SLEA-ORA(3) and SLEA-ORA(4) achieve the lowest average number of IP hops and clearly outperform IRA.

We also observe that the optimal $\mathcal{C}$ changes with the traffic load as shown in the figure. This implies that a dynamic SLEA will be more efficient than a static one. Such a dynamic control could be realized by monitoring the network traffic load at all nodes and properly adjusting the parameter "$\mathcal{C}$" according to the guidelines established in our paper. It is obvious that such a dynamic adjustment would complicate network management. It can also be noticed that the optimum "$\mathcal{C}$" does not change significantly when the traffic load varies over a wide range, making the use of static SLEA possible as well.

B. Limited Number of Ports: SLEA-IRA Versus IRA

From the above results, we find that the SLEA with carefully selected $\mathcal{C}$ can improve the performance of ORA significantly. A question then arises: "Can IRA also benefit from SLEA?" We therefore apply SLEA in IRA and evaluate the corresponding performance as plotted in Fig. 7. Note that the layered graph model and the modified Dijkstra's algorithm in Section IV can be easily extended to support IRA.

Fig. 7(a) shows that the SLEA can also improve the W-Eff of IRA. SLEA-IRA with a smaller $\mathcal{C}$ has a higher W-Eff. However, the improvement of W-Eff achieved by SLEA in IRA is less significant than that in ORA. Obviously, SLEA-IRA is equal to IRA when $\mathcal{C} = \infty$. However, there is almost no improvement in P-Eff when $\mathcal{C} < \infty$, as shown in Fig. 7(b). Accordingly, IRA cannot benefit from SLEA in terms of BBR as shown Fig. 7(c). Also, with decreasing $\mathcal{C}$, the average number of IP hops of LSP increases in Fig. 7(d). Hence, our conclusion is that the SLEA does not improve the performance of IRA when the number of the ports in each node is limited.

This scenario is mainly due to the fundamental difference between ORA and IRA. In order to save the number of ports, ORA always first tries to find a path using the existing lightpaths. If

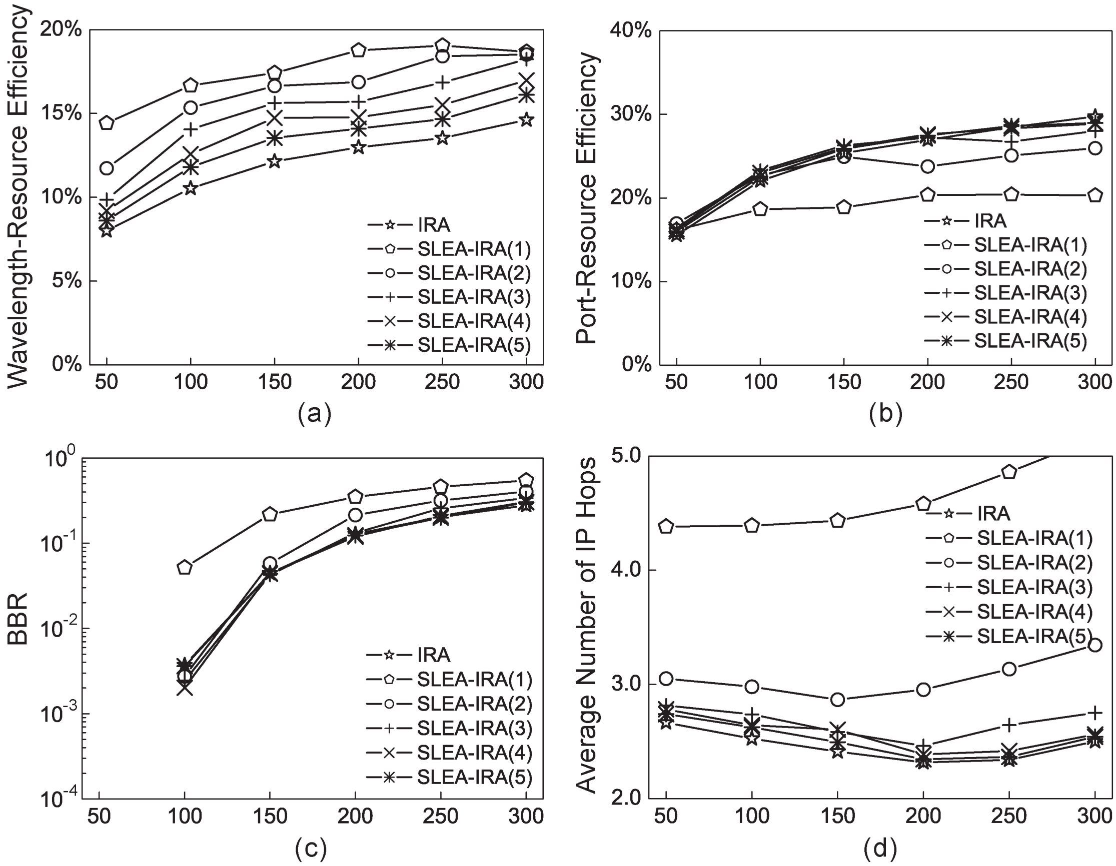

Fig. 7. Network performance versus network traffic load with $\Delta = 0.3$ for SLEA-IRA and IRA. (a) W-Eff. (b) P-Eff. (c) BBR. (d) Average number of IP hops.

TABLE I
RATIO OF OPTICAL HOP COUNTS OF THE LIGHTPATHS SET UP FOR THE REQUESTS WHOSE BANDWIDTH REQUIREMENTS ARE LESS THAN THE FULL WAVELENGTH BANDWIDTH WHEN $\Delta = 0.3$ AND $\rho = 100$ ERLANG

Hop Counts	1	2	3	4	5	6	7	8	9	$\geq$ 10
IRA	83.9%	7.62%	3.5%	1.9%	1.28%	0.92%	0.49%	0.24%	0.12%	0%
ORA	7.37%	13.4%	18.2%	12.6%	14.2%	14.7%	6.58%	4.74%	4.47%	3.68%

the effort fails, it then sets up a direct lightpath in the optical layer. As a result, ORA tends to establish a significant number of long lightpaths. However, IRA can route the request in the IP layer and through different optical layers, enabling efficient use of the wavelength resource. Hence, IRA tries to utilize the existing lightpaths and may create several short lightpaths as long as there are available ports in the nodes. Consequently, when the bandwidth requirement of a request is less than the full wavelength bandwidth, the number of long lightpaths created by IRA is much smaller than that by ORA. As shown in Tables I and II, 60.97% of the lightpaths established by ORA are longer than 4, whereas only 4.95% of the lightpaths set up by IRA are longer than 3. This shows that IRA tends to set up short lightpaths, which is why IRA cannot benefit from SLEA since its key idea is to prevent setting up long lightpaths with low utilization efficiency.

The average number of IP hops of each algorithm initially goes down for increasing load and then increases with $50 \leq \rho \leq 300$ Erlang, as shown in Figs. 6(c) and 7(c). However, it should be noted that the number of IP hops depends on many other factors, such as network topology, routing strategy, and request granularity. Therefore, such trends could change under other network conditions.

TABLE II
AVERAGE NUMBER OF OPTICAL HOPS OF THE LIGHTPATHS ESTABLISHED FOR THE REQUESTS WHOSE BANDWIDTH REQUIREMENTS ARE LESS THAN THE FULL WAVELENGTH BANDWIDTH WHEN $\Delta = 0.3$

Traffic Load (Erlang)	50	100	150	200	250	300
IRA	1.35	1.36	1.39	1.51	1.84	2.24
ORA	4.46	4.67	4.47	3.99	3.68	3.51

C. *Effect of Number of Ports*

We study the performances of SLEA-ORA and IRA versus the variable Δ in Fig. 8 with $\rho = 200$ Erlang. The results show that IRA has a lower BBR than ORA and SLEA-ORA(inf) in almost the full range of Δ, and the deviation between IRA and ORA increases drastically with the value of Δ. When $\Delta \geq 0.4$, the BBR of ORA is almost 100 times larger than that of IRA.

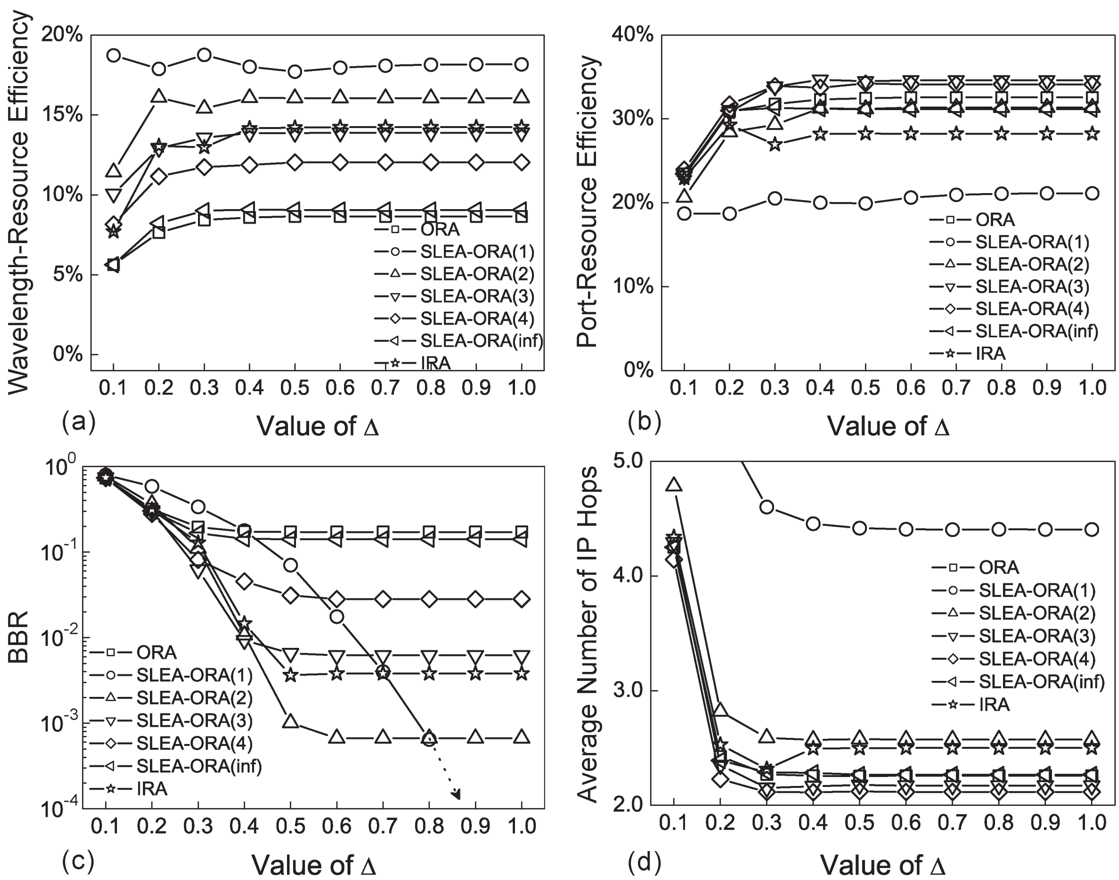

Fig. 8. Network performance versus value of Δ with the offered load $\rho = 200$ Erlang. (a) W-Eff. (b) P-Eff. (c) BBR. (d) Average number of IP hops.

We also find that with respect to the BBR, there is an optimal value of the optical hop constraint denoted as $\mathcal{C}_{\rm opt}^{\rm BBR}$ under a given Δ.[1] For example, $\mathcal{C}_{\rm opt}^{\rm BBR} = 4$ when $\Delta = 0.1-0.2$, $\mathcal{C}_{\rm opt}^{\rm BBR} = 3$ when $\Delta = 0.3-0.4$, and $\mathcal{C}_{\rm opt}^{\rm BBR} = 2$ when $\Delta = 0.5-0.7$. This shows that the value of $\mathcal{C}_{\rm opt}^{\rm BBR}$ decreases with increasing Δ, which is consistent with intuition. The large Δ means that the ports are sufficient and W-Eff plays an important role. As shown in Fig. 8, when $\Delta > 0.6$, the number of available ports is not the bottleneck for almost any algorithm, because most of the BBRs do not decrease with increasing Δ. In this case, the wavelength is the network resource of concern. Therefore, an algorithm with a high W-Eff will likely perform well when Δ is large, which contributes to the fact that the deviation between IRA and ORA increases significantly with Δ. On the other hand, when Δ is very small, the port is the resource of concern, and the algorithm with a high P-Eff will likely perform well. For example, when $\Delta = 0.1$, the BBR of IRA is even higher than that of ORA because the P-Eff of IRA is lower than that of ORA. Therefore, it is clear that the optimal optical hop constraint $\mathcal{C}_{\rm opt}^{\rm BBR}$ is related to the network configuration.

SLEA-ORA(1) always has the highest W-Eff but the lowest P-Eff. As Δ increases, SLEA-ORA(1) decreases its BBR faster than other algorithms. SLEA-ORA(1) achieves the lowest BBR (i.e., 0%) when $\Delta \geq 0.9$. Unfortunately, SLEA-ORA(1) has the largest average number of IP hops, which is usually not acceptable in practical applications. Therefore, SLEA-ORA(2) is more applicable than SLEA-ORA(1) when Δ is large. If the traffic is not sensitive to the transmission delay, SLEA-ORA(2) will be a good option. For traffic that requires low latency, SLEA-ORA(3) is more suitable. SLEA-ORA(3) outperforms IRA in terms of BBR when $\Delta \leq 0.4$ while IRA is slightly better than SLEA-ORA(3) when $\Delta \geq 0.5$. SLEA-ORA(3) always has a lower latency than IRA, as shown in Fig. 8(d). This indicates that SLEA-ORA could be more attractive than IRA regardless of Δ as long as the optical hop constraint is carefully selected according to the network configuration.

VI. Conclusion

An approach termed the short lightpath establishment approach (SLEA) is introduced to improve the performance of overlay routing algorithm (ORA) in Internet protocol/wavelength-division-multiplexing (IP/WDM) networks without introducing additional computational complexity. The analysis and simulation show that SLEA-ORA can efficiently utilize the network resource of concern if an optical hop constraint is selected carefully according to the network configuration. In practical applications where low-bandwidth requests dominate over high-bandwidth ones, SLEA-ORA with an optimal optical hop constraint could even outperform integrated routing

[1]Note that $\mathcal{C}_{\rm opt}^{\rm BBR}$ is not necessarily equal to $\mathcal{C}_{\rm opt}^{\rm P\text{-}Eff}$, as shown in Fig. 8, because the BBR of an algorithm is related to both its W-Eff and P-Eff.

algorithm (IRA) in terms of the bandwidth-blocking ratio (BBR) and the average number of IP hops. In addition, SLEA-ORA requires much less information exchange in the networks than IRA. Therefore, the proposed SLEA could make ORA more favorable than IRA as long as the optical hop constraint is optimized.

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