Adaptive Differentiated Integrated Routing Scheme for GMPLS-based Optical Internet

Wei Wei, Qingji Zeng, Tong Ye, and David Lomone

Abstract: **A new online multi-layer integrated routing (MLIR) scheme that combines IP (electrical) layer routing with WDM (optical) layer routing is investigated. It is a highly efficient and cost-effective routing scheme viable for the next generation integrated optical Internet. A new simplified weighted graph model for the integrated optical Internet consisted of optical routers with multi-granularity optical-electrical hybrid switching capability is firstly proposed. Then, based on the proposed graph model, we develop an online integrated routing scheme called differentiated weighted fair algorithm (DWFA) employing adaptive admission control (routing) strategies with the motivation of service/bandwidth differentiation, which can jointly solve multi-layer routing problem by simply applying the minimal weighted path computation algorithm. The major objective of DWFA is fourfold: 1) Quality of service (QoS) routing for traffic requests with various priorities; 2) blocking fairness for traffic requests with various bandwidth granularities; 3) adaptive routing according to the policy parameters from service provider; 4) lower computational complexity. Simulation results show that DWFA performs better than traditional overlay routing schemes such as optical-first-routing (OFR) and electrical-first-routing (EFR), in terms of traffic blocking ratio, traffic blocking fairness, average traffic logical hop counts, and global network resource utilization. It has been proved that the DWFA is a simple, comprehensive, and practical scheme of integrated routing in optical Internet for service providers.**

Index Terms: **Generalized multi-protocol label switching (GMPLS), integrated routing, optical Internet, optical router, quality of service (QoS).**

I. INTRODUCTION

Optical Internet (i.e., IP/WDM network) is becoming a common switching/transport platform for most of network service providers, which will simultaneously offer multiple service classes capable of supporting both high-speed real-time and non-real-time traffic flows. The current rapid pace of developments in both IP networks and optical networks is inevitably bringing the two domains closer together [1]. For the next generation optical Internet (NGOI) architecture, solutions such as overlay model, peer model, and integrated model have been proposed, respectively [2], [3]. By using a unified control plane based on generalized multi-protocol label switching (GMPLS) [4], integrated (or peer) IP over WDM networks can make more efficient use of network resources both at IP layer and optical layer. As shown in Fig. 1, we believe that a high performance and scalable optical Internet architecture should be implemented as integrated model.

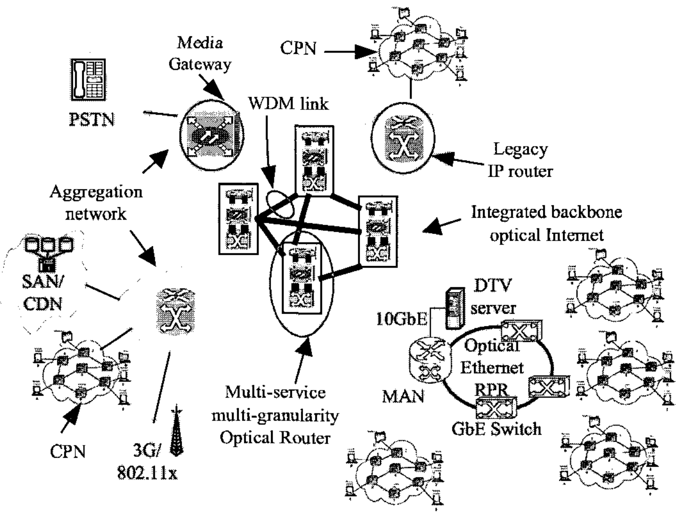

Fig. 1. The next generation integrated optical Internet architecture.

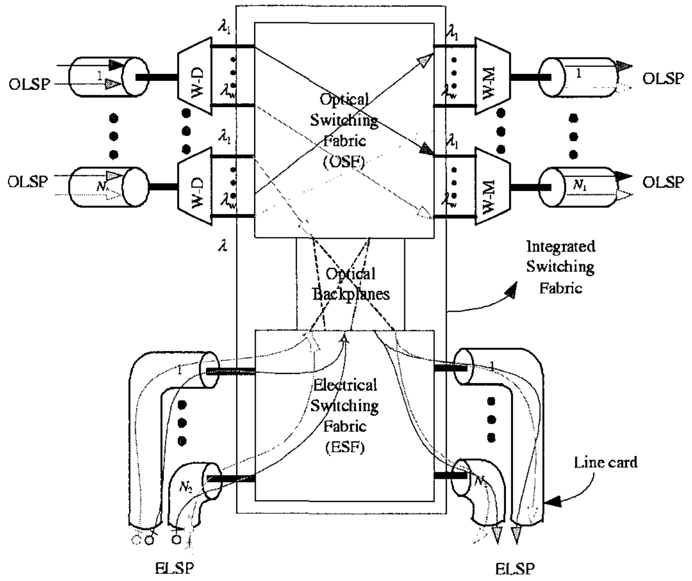

Fig. 2. Optical router model with multi-granularity switching capability.

The GMPLS-based multi-service optical routers with multi-granularity switching capability in Fig. 1 can dramatically improve network's forwarding performance for their functionalities of flexible traffic aggregation/grooming, dynamic virtual topology adaptation/reconfiguration, optical bypassing, etc. As

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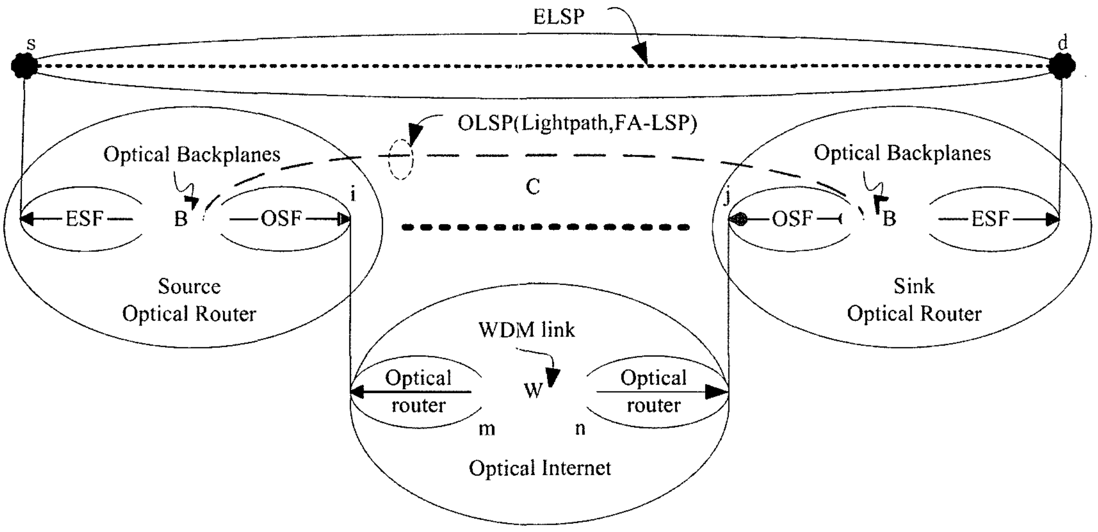

Fig. 3. The unified vision for multi-layer integrated LSP routing.

shown in Fig. 2, we propose a node structure for this kind of optical router. We claim that such router structure has to be hybrid (i.e., neither all-optical nor pure electrical) for the considerations of network cost and performance. Note that in Fig. 2 OLSP denotes optical label switching path (i.e., lightpath or forwarding adjacency LSP (FA-LSP)), and ELSP denotes electrical label switching path (i.e., low-speed traffic flows).

The dynamic routing/provisioning of traffic connections with arbitrary bandwidth request is becoming one of key issues for carriers. In current overlay IP over WDM network model, sequential routing (i.e., overlay routing) scheme has been employed to treat IP and optical layers separately. For example, when a traffic connection request arrives, overlay routing scheme usually conducts the following two steps in sequence: 1) Route the request on existing lightpaths (virtual topology); 2) if step 1 fails, create a new single-hop lightpath on the WDM links (physical topology). For the motivations of getting better resource usage and improving network throughput performance, multi-layer integrated routing (MLIR) techniques taking into account the combined topology and resource usage information of both layers have been received much attention in research area [3]–[20]. In MLIR framework, the physical links in optical layer and logical links (lightpaths) in IP layer are considered jointly for path selection (it only needs one step). Specifically, the proposed integrated optical Internet architecture depicted in Fig. 1 and the multi-granularity optical router depicted in Fig. 2 will help to implement high performance MLIR scheme that is more efficient due to the flexibility in path selection, which is illustrated in Fig. 3.

Generally, the MLIR problem can be decomposed into three sub-problems: 1) Virtual topology design (VTD); 2) routing and wavelength assignment (RWA); 3) constrained-based routing (CBR). The iterative optimization flowchart is shown in Fig. 4 for static MLIR solutions. However, for the dynamic MLIR problem in GMPLS-based integrated optical Internet, these three sub-problems can be treated in a unified manner and solved simultaneously [6], [10], [12], [15].

In this paper, based on a new integrated graph representation and a flexible routing strategy that selects paths taking into account the traffic priority and bandwidth granularity to fulfill the quality of services (QoS) requirements of the incoming request, an adaptive differentiated integrated routing scheme for GMPLS-based optical Internet is proposed. The incoming traffic requests are classified based on their priorities and bandwidth granularities. Different routing policies which route requests in either single-layer (physical or virtual) topology or in the integrated topology depending on the traffic classes are employed.

The rest of this paper is organized as follows. Section II investigates related work and Section III presents a new weighted graph model for integrated optical Internet. Section IV develops an online integrated routing scheme called differentiated weighted fair algorithm (DWFA). We provide the numerical results of DWFA in Section V. Section VI concludes the paper.

II. RELATED WORK

The major motivation of integrated routing in optical Internet is the possibility of achieving better network resource utilization than overlay routing. Recently, a single integrated control plane in the framework of GMPLS based on IP-like signaling and routing mechanisms is being developed to define a standard interface permitting optical routers to exchange resource information and to dynamically provision generalized LSP (GLSP) requests [4]. This makes it feasible to whether an arriving GLSP request can either be routed over the existing virtual topology or physical topology. To obtain topology and resource usage information for integrated routing, additional routing extensions to indicate resource properties of optical routers (e.g., grooming capability) may also be needed. In [5], the authors firstly proposed a draft on the requirements of the MLIR extensions.

An amount of previous studies on the problem of MLIR in IP/WDM networks (without protection capability [6] and with protection capability [7]) and SDH/WDM networks have already been conducted. The problem of MLIR in SDH/WDM

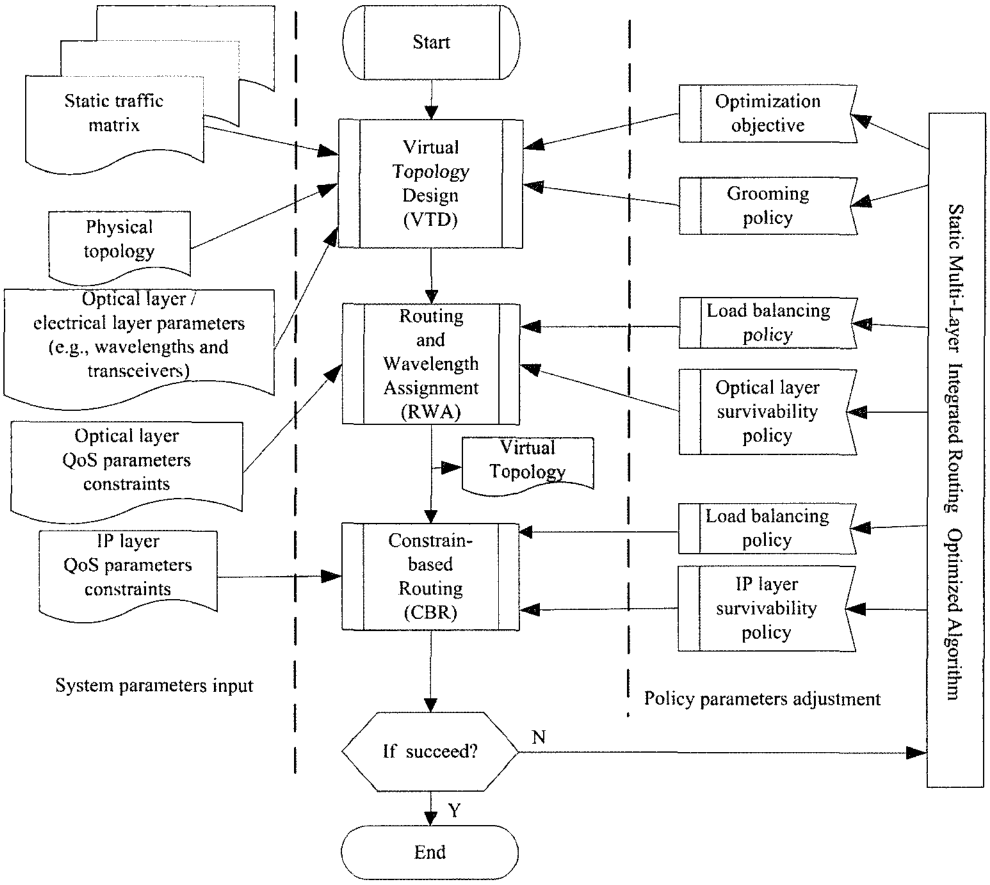

Fig. 4. The structure of multi-layer integrated routing (MLIR) problem.

networks is also called traffic grooming [8]–[11][1], which is to pack discrete time division multiplexing (TDM) circuits into wavelength channels to minimize the number of electronic add-drop multiplexer (ADM). As MLIR problem is NP-hard [10], [11], many heuristic methods have been developed [6]–[20]. The most commonly used is the integrated minimum hop (IMH) algorithm [6], in which the path with the least number of links between the ingress and egress router is chosen. The drawback of the IMH algorithm may result in higher blocking probability and inefficient network resource utilization since it always selects the shortest path in network topology regardless of network resource state. M. Kodialam *et al.* [6] developed the maximum open capacity routing algorithm (MOCA) that was to pick paths that did not interfere too much with potential future setup requests between other ingress egress pairs. In MOCA, the IP/WDM network was modeled as a layered graph for combined path computation, where wavelengths on a link were separated into different graph edges. The MOCA was used to dynamically route the connection request on the layered graph that was modified after every successful connection. The idea of MOCA is a good one for the critical link computation in path selection, but it has three shortcomings: 1) No consideration of transceivers resource constraints; 2) traffic requests limited only to some specific ingress and egress router pairs, which need to be known in advance; 3) too complex for real usage.

Y. Ye *et al.* [7] presented a simple integrated provisioning/protection scheme to dynamically allocate restorable bandwidth guaranteed paths in IP/WDM networks, which take advantages of GMPLS to provide end-to-end survivability by incorporating network state information from both layers into protection path allocation. Simulation results showed that the proposed protection approach could efficiently improve network utilization. S. Subramaniam *et al.* [8] studied the problem of grooming, routing, and wavelength assignment (RWA) to minimize resources (i.e., wavelengths and ADMs) when there was a mix of survivable and non-survivable circuits in optical networks. A survivable circuit is defined as one which needs to be restored after failure and a non-survivable circuit as one which need not to be (for example, those carrying low priority traffic). R. Srinivasan *et al.* [9] proposed and studied a request-specific integrated routing scheme called available shortest path routing (ASPR) in WDM grooming networks. ASPR considered the capacity requirement of a request and selected the shortest path among those that could accommodate the request. It was shown through simulations that ASPR enhanced the performance of the network with respect to utilization and fairness metrics as compared to the widest-shortest path routing (WSPR) and shortest-widest path routing (SWPR). K. Zhu *et al.* [11] investigated the problem of efficiently provisioning connections of different bandwidth granularities in a heterogeneous WDM

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[1] In our views, traffic grooming is completely the same as integrated routing in IP/WDM networks.

mesh network through dynamic traffic grooming schemes under traffic engineering principles. The authors extended an existing generic graph model (called auxiliary graph proposed in [10] by H. Zhu *et al.*) to perform efficient traffic grooming and achieved different traffic engineering objectives through simple shortest path computation algorithms. E.C. Tien *et al.* [12] developed a new network graph model that integrated various network resources such as residual bandwidth, wavelengths, ports, and also o-e-o conversions, which was different from other conventional graph representations (e.g., [6]). They also developed a threshold-protection-based routing algorithm, which admitted high-priority LSPs in preference over low-priority LSPs and satisfied the bandwidth and o-e-o constraint requirements. J. Comellas *et al.* [13] presented an integrated routing strategy that took into account constraints and dynamic occupancy of both IP and optical layers, using shortest path routing algorithm with the path weight being the number of total or extra light path hops or wavelength links required to establish a connection. Simulations showed the proposed scheme could improve network performance over fixed routing strategies.

In [14], the authors developed comprehensive unified constraint-based routing algorithms combining both IP routing and optical resource to provision "sub-wavelength" circuits (low-rate traffic streams). Constraint-based routing was further augmented by dynamically routing both an active and another alternate link/node-disjoint backup path at the same time in order to provision a given connection request. B. Wang *et al.* [15] developed an integrated online algorithm for dynamic routing of bandwidth guaranteed LSPs in IP/WDM networks. The proposed algorithm considered not only the importance of critical links, but also their relative importance to routing potential future LSP set-up requests by characterizing their normalized bandwidth contribution to route future LSP requests with bandwidth requirements. Moreover, link residual bandwidth information that captured the link's capability of routing future LSPs was also incorporated into route calculation. Simulation results showed that the proposed algorithm performs better than IMH and MOCA in terms of the number of LSP set-up requests rejected and the total available bandwidth between router pairs. X. Niu *et al.* [16] proposed and investigated three connection admission control policies for the establishment of LSPs and argued that there existed a lower bound for the number of add/drop ports of OXCs for the network to achieve almost the best LSP blocking performance. The authors in [17] studied the capacity fairness of existing dynamic wavelength assignment algorithms and proposed a simple admission control algorithm to attain fairness in capacity. In [18], the authors proposed two dynamic optical path generation algorithms: O-LSP creation first (OCF) routing strategy and O-LSP creation last (OCL) routing strategy. K. Zhu *et al.* [19] used a reachable graph capturing all possible links for a given connection request between any two nodes and proposed two algorithms to compute a route: Two-layered route-computation (TLRC) and single-layered route-computation (SLRC) scheme. The authors concluded that different grooming policies and route-computation algorithms needed to be used under different network state. The work in [20] applied the different grooming strategies in parallel in their weighted integrated routing (WIR) algorithm without the need for a full integrated view of the network, which probed rating information on different paths from both layers and selected a path based on its cost.

In our views, most of previous work on integrated routing (or traffic grooming) have the following limitations: 1) Fail to consider the real time traffic with high-priority request (without considering service differentiation, e.g., [6]–[8], [10], [13]–[14], and [16]-[20]); 2) lack of blocking fairness for high bandwidth traffic requests (e.g., [9], [11], [12], and [15]); and 3) furthermore, implementation is too complex for service providers (e.g., [6]).

Online differentiated integrated routing problem is now of great interests, because carriers are starting to offer dynamic GLSP provision service as a competitive way. We think the major challenge on integrated routing problem is to design a simple and practical scheme that achieves efficient resource utilization while it satisfies QoS demands. The remarkable difference between those previously considered integrated routing schemes and the scheme considered in this paper are that: 1) We consider the routing of GLSPs taking into account the combined knowledge of resource and topology information in a new network graph representation; 2) we consider the service differentiation and bandwidth differentiation for the admission control of multi-service multi-granularity traffic requests. Clearly, our proposed dynamic integrated routing scheme will be more efficient and robust than those previous methods.

III. SIMPLIFIED GRAPH MODEL FOR OPTICAL ROUTER AND OPTICAL INTERNET

In this section, we present a new weighted graph model to represent integrated optical Internet and explain the modeling of cost (weight) using various network resources such as wavelengths, lightpaths, backplanes (transceivers), and switching fabrics. To illustrate the weighted graph model, we firstly propose a new simplified graph representation for various node structures. As depicted in Fig. 5, the sub-node EI denotes electrical (packet) input port, the sub-node EO denotes electrical output port, and the link between EI and EO denotes electrical switching fabrics (i.e., packet switching fabric, see Fig. 2). The sub-node OI denotes optical (wavelength) input port, the sub-node OO denotes optical output port, and the link between OI and OO denotes optical switching fabrics (i.e., wavelength switching fabric, see Fig. 2). The links between OI and EI (including OO and EO) denote optical backplanes (e.g., tunable transceiver arrays, see Fig. 2). Fig. 5(a) denotes the abstract model of our proposed optical router node structure, Fig. 5(b) represents the abstract model of OXC structure (without packet switching capability), Fig. 5(c) denotes the abstract model of IP router with WDM interface, and Fig. 5(d) denotes the abstract model of traditional IP router. Note that in Fig. 5, s and d denote the source and sink of traffic request (i.e., ELSP), respectively.

Based on the node graph model in Fig. 5, for example, we provide a new simplified graph model for a typical integrated optical Internet as shown in Fig. 6. Assuming that there is an ELSP request from node 5 to node 2, the path found comprises seven links (four kinds of link) in the integrated network topology. The basic idea in Fig. 6 is to represent the entire optical Internet with

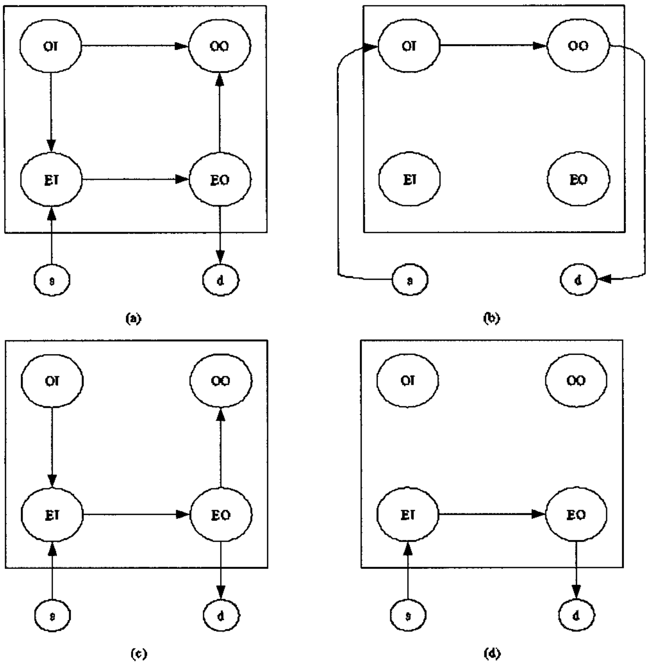

Fig. 5. The simplified graph model for various node structures.

all types of sub-nodes and links in a simplified (compared to the one in [6], [10], and [12]) integrated graph. In [6], the network state is represented by a layered-graph that models the residual lightpath capacity and wavelength usage only. It does not depict the constraint of transceivers (i.e., optical backplanes bandwidth which denotes electrical grooming capacity in our node model). Although in [10] and [12] the transceivers usage is modeled, it seems too complex for the large number of wavelengths because of layered-graph model. Compared with those graph representations in [6], [10], and [12], our proposed graph representation has better scalability for using link bundle concept [4], in such a case, less link state information is maintained and disseminated when realizing distributed integrated routing algorithm.

When an ELSP request arrives, the routing process will select the minimum weighted path for this request according to the network current resource state in integrated graph topology (ITG). We suggest that each kind of link is weighted as follows from the viewpoint of load balancing, which unify various link metrics:

- WDM link weights:

$$w_1 = \begin{cases} \infty & \lambda = 0 \\ \alpha & \lambda = 1 \\ -\alpha \log(1 - \frac{1}{\lambda}) & W \geq \lambda > 1. \end{cases} \tag{1}$$

In (1), λ denotes the number of residual wavelengths of a WDM link, α denotes weight coefficient, and W denotes the total wavelengths of a WDM link. The coefficient α is configurable according to system parameter of wavelength bandwidth, so the weight (w_1) of a physical link is related with α, and the number of residual wavelengths of a physical link, which is equivalent to the total bandwidth of a physical link.

- Lightpath (OLSP/FA-LSP) weights:

$$w_2 = \begin{cases} \infty & b = 0 \\ \beta & b = C \\ \beta * \frac{C}{b} & C > b > 0. \end{cases} \tag{2}$$

In (2), b denotes the residual bandwidths (Mb/s) of a lightpath, β denotes weight coefficient, and C denotes wavelength rate (e.g., for $OC - 48/STM - 16$, $C = 2500$ Mb/s).

- Optical backplane link weights:

$$w_3 = \begin{cases} \infty & g = 0 \\ \rho & g = B \\ \rho * \frac{B}{g} & B > g > 0. \end{cases} \tag{3}$$

In (3), g denotes the residual bandwidths (Mb/s) of optical backplanes (i.e., transceivers bandwidth) in an optical router, ρ denotes weight coefficient, and B denotes total bandwidth of optical backplanes.

- Optical switching fabrics link weights:

$$w_4 = \sigma. \tag{4}$$

Usually, optical switching fabric is non-blocking. So we only define a constant σ for the weight coefficient of optical switching fabric link.

- Electrical switching fabrics link weights:

$$w_5 = \omega. \tag{5}$$

In (5), ω is a constant that denotes electrical switching fabric link weight when we assume electrical switching fabric is non-blocking.

The weight coefficients from (1) to (5) reflect two basic meanings: 1) The relative preference (cost) of various kinds of network resource (e.g., optical backplanes bandwidth, free wavelength, and lightpath residual bandwidth) in the path selection, 2) the global load balancing between various layers/links (i.e., various links in electrical layer and optical layer). By modifying the weight coefficients according to the requirements of various service providers and then by running the Dijkstra's algorithm on the simplified weighted graph to find the shortest path, different routing schemes with different objectives can be realized.

IV. DIFFERENTIATED WEIGHTED FAIR ALGORITHM

Generally, when a request arrives in a given ingress optical router, various routing strategies can be applied:

- Single-hop routing on existing lightpaths in virtual topology graph (VTG);
- multi-hop routing on existing lightpaths in VTG;
- single-hop routing on a new lightpath in physical topology graph (PTG);
- multi-hop routing on new lightpaths in the PTG;
- combined multi-hop routing on new and existing lightpaths in the integrated topology graph (ITG).

On one hand, different routing strategies reflect different optimization objectives (e.g., network resource utilization and traffic blocking ratio) for various service providers[2]. On the other

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[2] Different performance optimization objectives can be achieved by modifying the sequence of routing operations.

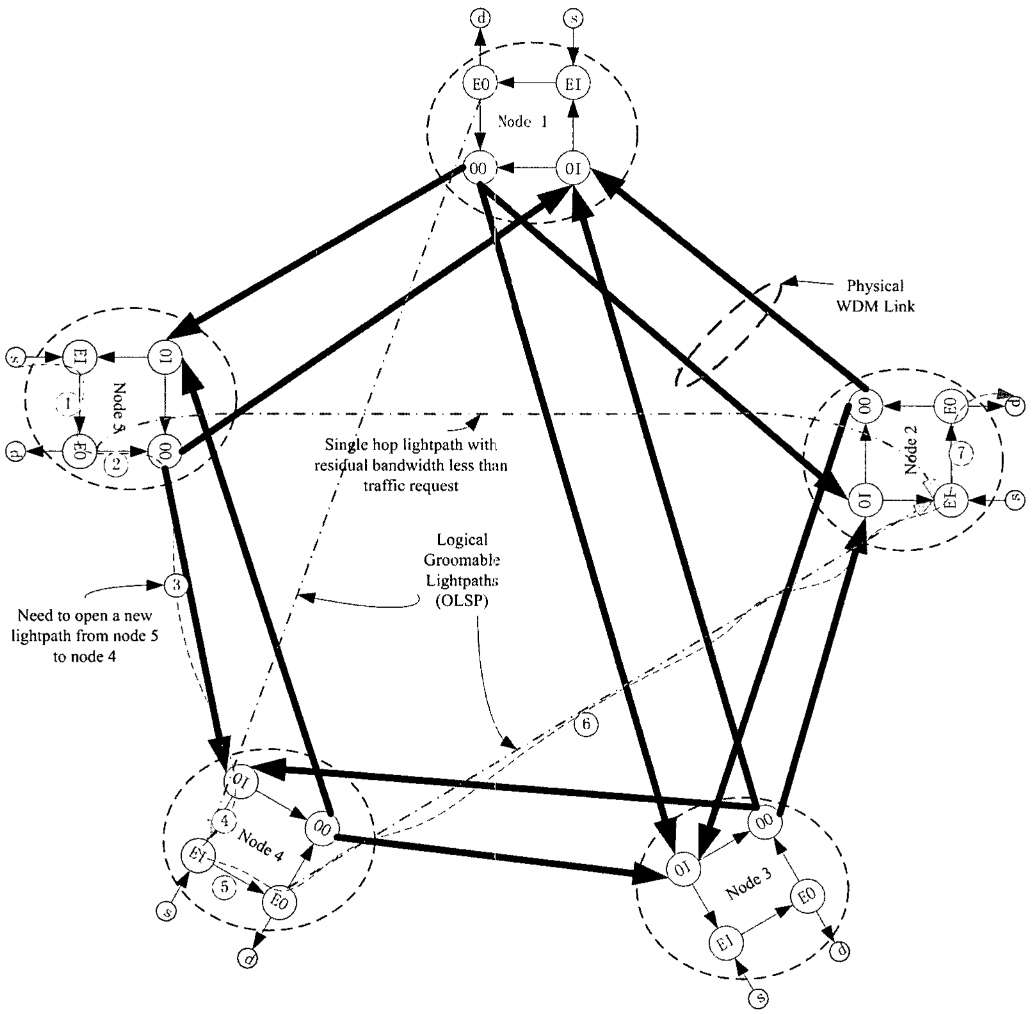


Fig. 6. The simplified graph model for a integrated optical Internet.

Table 1. Adaptive differentiated integrated routing scheme.

Parameter	(HP,HB) ELSP request	(HP,LB) ELSP request	(LP,HB) ELSP request	(LP,LB) ELSP request
Routing policy	PTG-first routing	ITG-first routing	VTG-first routing	VTG-first routing
Logical hop-count limit	Yes (usually single-hop)	Yes	No	No
Bandwidth guarantee traffic blocking ratio requirement	Yes Lowest	Yes Lower	No Low	No Best-effort
Multi-path routing support	No	No	Yes	No
Typical traffic type	Streaming media service (e.g., VoIP trunks, DTV)	VPN service (e.g., tunnel, grid computing)	Data center service (e.g., FTP and storage applications)	Traditional low speed best-effort service

hand, the selected principle of routing strategies is also related with traffic QoS requirements (e.g., packet loss ratio, delay, and jitter), traffic bandwidth, node electrical processing capacity, etc. In this section, we develop an online integrated routing algorithm called differentiated weighted fair algorithm (DWFA) to route incoming ESLPs adaptively. Considering multi-granularity multi-priority ELSP requests in real networks, we classify incoming ELSPs into four QoS levels according to different request priorities and bandwidth granularities. For each kind of ELSP requests, we employ different routing policies as shown in Table 1.

The basic motivation in Table 1 is that high-priority (HP) traffic requests will get lower traffic blocking ratio and average logical hop counts than low-priority (LP) traffic requests, so end-to-end delay for HP traffic is relatively lower. Moreover, high-bandwidth (HB) traffic requests as well as low-bandwidth (LB) traffic requests with the same priority will enjoy nearly the same traffic-blocking ratio. Therefore, the proposed scheme can lead to a better tradeoff between network resource utilization and traffic blocking ratio/fairness for various types of traffic. We illustrate the DWFA as follows:

Input:
A network model $G(V,E,W,B,L)$, where $V(|V|)$ denotes the set of optical routers without wavelength conversion capabilities. $E(|E|)$ denotes the set of directed WDM links. $W(|W|)$ denotes the set of wavelengths per WDM link. $B(|B|)$ is the set of optical backplane bandwidth configuration per optical router. $L(|L|)$ is the set of lightpaths. An ELSP request between ingress and egress optical router pair $(s,\ d)$ is represented as $R(s,d,t,b)$, where t is its priority and b is its bandwidth requirement.
Output:
Return a set of path between s and d or NULL if no such paths are found.
Steps:
Step 1. Import system parameters such as $G(V,E,W,B,L)$ and construct various topology graph structure including PTG, VTG, and ITG.
Step 2. Update residual bandwidth of all links and compute the weights of all the links in the PTG, VTG, and ITG.
Step 3. Wait ELSP request setup/release message from traffic request module.
When an ELSP (HP, HB) request arrives, the DWFA does the following:
Step 301. Prune infeasible links which have residual bandwidth less than b in VTG, and check if there exists a single-hop lightpath between s and d. If yes, return the path. Otherwise, go to next step.
Step 302. Employ RWA algorithm (K-Shortest-Path and First-Fit) to establish a new single-hop lightpath in PTG between s and d. If succeed, return the path. Otherwise, reject the request.
When an ELSP (HP, LB) request arrives, the DWFA does the following:
Step 311. Prune infeasible links which have residual bandwidth less than b in ITG, and form a reduced ITG.
Step 312. Employ Dijkstra's algorithm to compute the minimum weighted path in the reduced ITG (It automatically opens wavelength paths when needs). If succeed, return the path. Otherwise, reject the request.
When an ELSP (LP, HB) request arrives, the DWFA does the following:
Step 321. Prune infeasible links which have residual bandwidth less than b in VTG, and form a reduced VTG.
Step 322. Employ Dijkstra's algorithm to compute the minimum weighted path with bandwidth guaranteed in the reduced VTG, and check if succeed. If yes (no NULL), return the path. Otherwise, go to next step.
Step 323. Employ K-Shortest-Path ($K=2$) algorithm to compute K paths (for traffic multi-path routing) in the origin VTG, and return the K paths, compute the bandwidth-blocking ratio.
When a low-priority low-bandwidth (LP, LB) ELSP request arrives, the DWFA does the following:
Step 331. Prune infeasible links which have residual bandwidth less than b in VTG, and form a reduced VTG.
Step 332. Employ Dijkstra's algorithms to compute the minimum weighted path in the reduced VTG, and check if succeed. If yes (no NULL), return the path. Otherwise, reject this request.
Step 4. Reserve resources, update statistical data and form the new VTG and ITG.
Step 5. If end, go to exit. Otherwise, go to step 2.

In terms of the complexity of DWFA, we analyze it in the worst case as follows. After transforming the original PTG network into the ITG network, the graph has $O(4\times|V|)$ nodes and the maximum number of links is equal to $(O(4\times|V|+|E|+|\frac{B}{C}|)$, where $4\times|V|$ is the number of added internal links in a node and $|\frac{B}{C}|$ is the number of added virtual links (i.e., lightpaths, C denotes a lightpath bandwidth). In the DWFA, the most complex route computation in the worst case is equal to the combination of: 1) Pruning $O(4\times|V|+|E|+|\frac{B}{C}|)$ links in ITG; 2) Dijkstra's algorithm in the reduced ITG; 3) K-shortest paths for traffic multi-path routing in VTG. So DWFA have a worst-case time complexity of $O(4\times|V|+|E|+|\frac{B}{C}|)+O((4\times|V|+|E|+|\frac{B}{C}|+4\times|V|\log(4\times|V|))+O(K\times|\frac{B}{C}|)$, where K is a constant, so the DWFA algorithm running time is linear in $O(|V|^2)$. As in previous work [6], the computation complexity of MOCA mainly depends on the calculation of the maxflow/min-cut algorithm which can be done in $O(|V||E|\log(|V|^2/|E|))$. The Dijkstra's algorithm runs in $O(|E|+|V|\log(|V|))$. So the complexity of MOCA becomes $O(|V||E|\log(|V|^2/|E|))+O(|E|+|V|\log(|V|))$, which is linear in $O(|V|^3)$. Therefore, the DWFA algorithm needs less computational complexity than the MOCA algorithm.

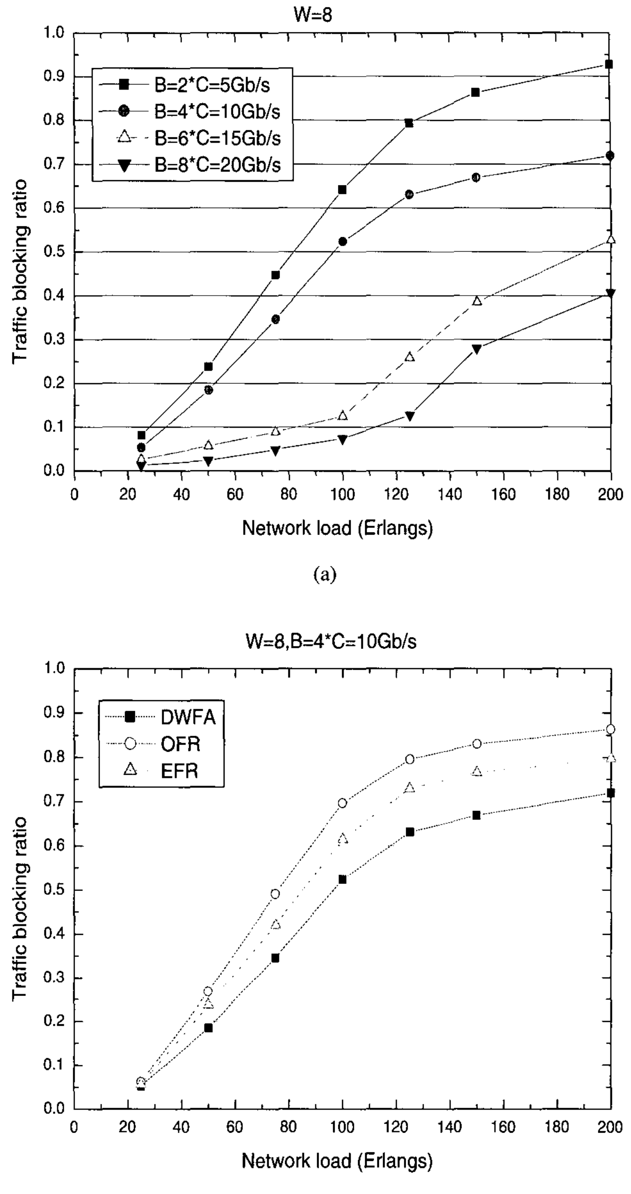
The DWFA is different from the earlier work-MOCA [6] in that we consider optical-layer resource and electrical-layer resource constraints as well as service differentiation and bandwidth differentiation. The basic difference between MOCA and DWFA is the graph representation for IP/WDM networks. In MOCA, the IP/WDM network state is represented by a layered-graph that models the residual bandwidth of lightpaths and wavelength usage only. It also assumes that sufficient numbers of transceivers (equivalently, optical backplanes bandwidth in the DWFA) are provided at nodes. On the contrary, we develop a weighted graph representation with a simplified (without layered-graph concept) but complete structure, which models not only lightpaths residual bandwidth and wavelength usage, but also optical backplane bandwidths (i.e., transceivers) usage. In addition, it is important to highlight that our scheme allows less complexity than MOCA because of no max-flow computation. It should also be noted that MOCA could be incorporated into the proposed DWFA scheme as a sub-algorithm for getting a more comprehensive routing solution.

In summary, DWFA has the following benefits. First, compared to the overlay routing schemes (e.g., optical-layer-first or electrical-layer-first routing), DWFA is more efficient because DWFA has a full overview of all the layers and that it can intelligently decide in which layer to select the appropriate path. As a result, the path found by DWFA leads to efficient utilization of the network resources and acceptance of increased number of requests. Second, by varying the adaptive routing strategies and algorithm parameters according to service provider specific requirement, we can achieve a more flexible integrated routing/provision scheme. Third, DWFA employs admission control to give preference to HP ELSPs and HB ELSPs, which ensures that resources are used efficiently and fairly. Finally, the proposed DWFA is relatively simple. However, DWFA needs the extra extensions of current GMPLS routing/signaling protocol (e.g., [5]), which are beyond the scope of this paper.

V. PERFORMANCE EVAULATIONS

In order to assess the need for service/bandwidth differentiation and effectiveness of the proposed integrated routing scheme, we analyze the performance of DWFA through simulation experiments. For numerical results, we also compare DWFA with optical-first-routing (OFR) and electrical-first-routing (EFR) schemes. OFR always route all kinds of traffic requests with bandwidth guaranteed on optical layer (i.e., physical topology) firstly, and if fail, then routing on electrical layer (i.e., virtual topology). EFR is contrary to OFR. We consider the typical NSFnet network topology with 14 nodes and 42 unidirectional fiber links, and $W = 8$ wavelengths per fiber. Each node is an optical router without wavelength conversion (see Fig. 2). The bandwidth of a wavelength is assumed to be $C = 2500$ units (one unit is equal to 1 Mb/s here). Optical backplanes bandwidth in an optical router $B = (2, 4, 6, 8) \times C = (5, 10, 15, 20)$ Gb/s. Connection requests $R(s, d, t, b)$ are assumed to be arrived randomly following a *Poisson* process with arrival rate φ and the connection holding time follows a exponentially distributed with mean $\frac{1}{\mu}$, so the network load is $\frac{\varphi}{\mu}$ Erlangs. The destination node is selected uniformly among all nodes except the source node. Each request bandwidth b of uniformly distributed between (1, 2500) units. Bandwidth control threshold $BCT = \frac{1}{2} \times C = 1250$ units. Each request priority of $R(s, d, t, b)$ is randomly distributed between LP and HP. The weight coefficients for various types of links for minimum weighted path computation are typically configured as $\alpha = 2500$, $\beta = 50$, $\rho = 10$, $\delta = 1$, $\omega = 10$. These weight coefficients are based on the relative preference of physical links, virtual links and transceivers for load balancing between optical layer and electrical layer in path selection. These coefficients are configurable according to system parameters such as W, B, C and service provider's policies. The number of alternate paths for K-shortest path computation $K = 2$. The numbers of are generated up to 10^6. In our simulation studies, we focus on three performance metrics: 1) QoS routing performance metrics including traffic blocking ratio and average traffic logical hop counts; 2) traffic blocking fairness for various bandwidth granularity traffic; and 3) average network resource utilizations.

We first show the simulation results of traffic blocking ratio (accepted bandwidth over total requested bandwidth) in Fig. 7. Fig. 7(a) shows the traffic blocking ratio simulation results of DWFA under various optical backplane bandwidth constraints, which indicates how the optical backplanes bandwidth affects traffic blocking ratio. From the Fig. 7(a), we can find two indicant points: 1) When network traffic load increases, traffic blocking ratio will also increase; 2) when B increases, traffic blocking ratio will decrease. This is because the optical backplane bandwidth of optical router has great influence on traffic blocking ratio. Moreover, we compare the simulation results of traffic blocking ratio of various routing schemes in Fig. 7(b). We can find that our proposed DWFA gets better traffic blocking performance than OFR and EFR schemes. This is because DWFA can conduct traffic grooming in electrical layer and traffic bypassing in optical layer intelligently according to the adaptive routing strategies. DWFA is more efficient because DWFA has a full overview of all the layers and that it can intelligently decide in which layer to select the appropriate path. Thus, the path found by DWFA leads to the acceptance of increased number of requests.



(a)

(b)

Fig. 7. Performance simulation results of traffic blocking ratio vs. network load.

Fig. 8 illustrates the simulation results of traffic blocking ra-

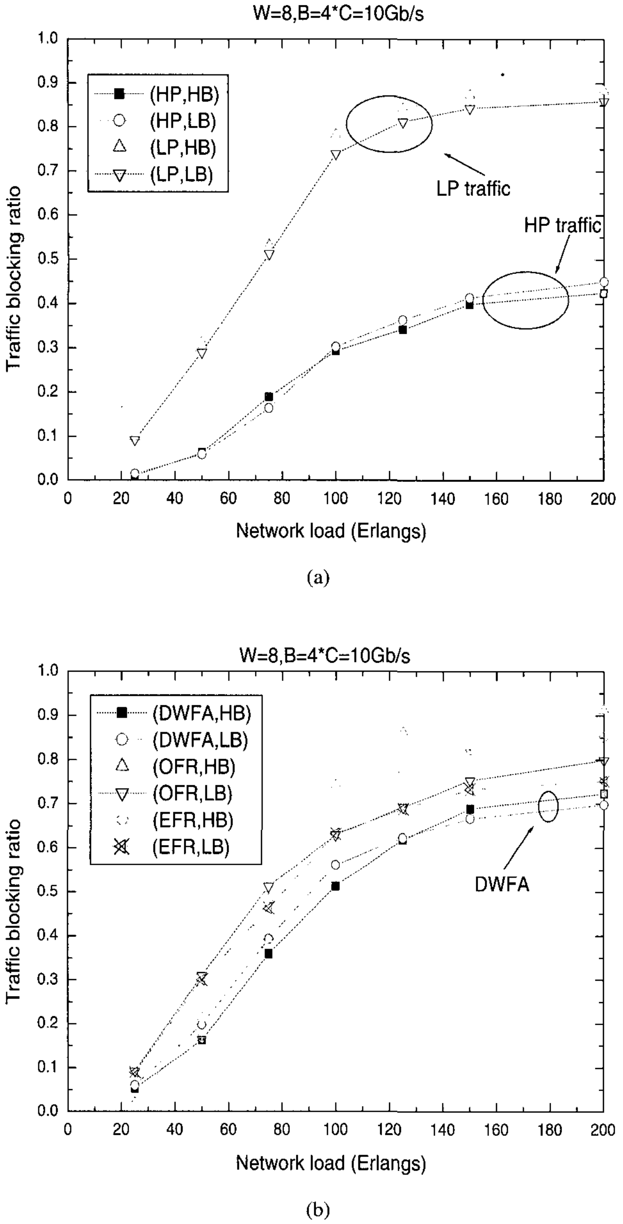


Fig. 8. Performance simulation results of traffic blocking ratio for different kinds of connections.

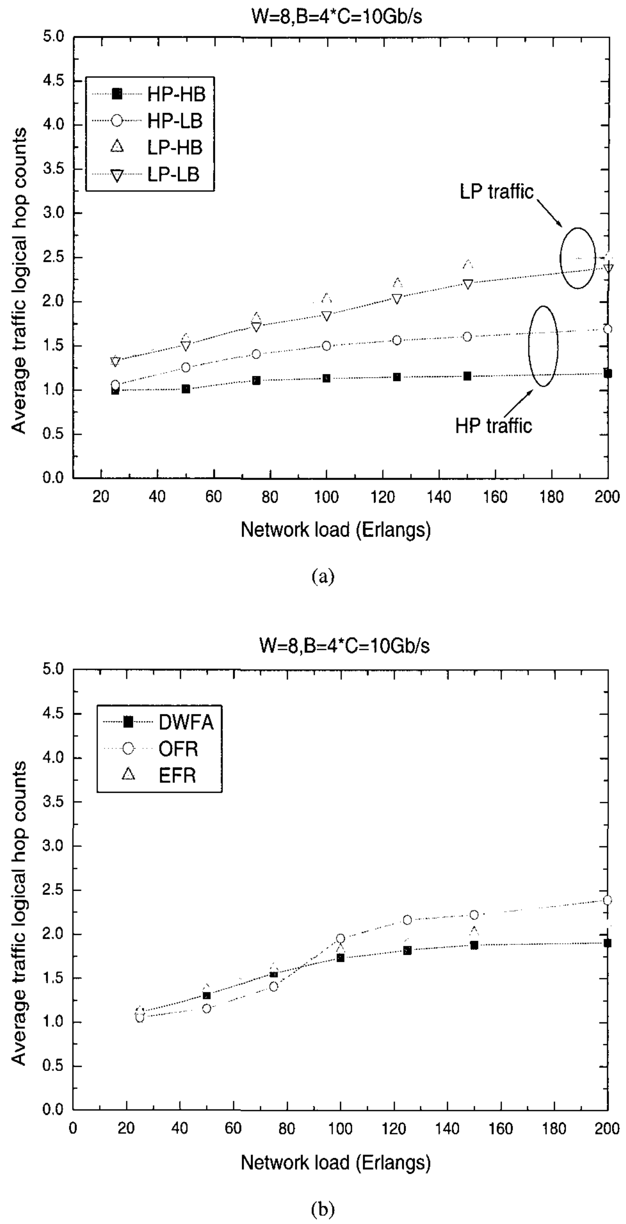


Fig. 9. Performance simulation results of average logical hop counts for different kinds of connections.

tio for different kinds of connection requests. Generally, since LB requests require small bandwidth, they are more likely to be accepted than HB requests that require large bandwidth. But from the Fig. 8(a) of the simulation results of DWFA, we can find that: 1) HP traffic blocking ratio is far less than LP traffic blocking ratio; 2) with the same priority, HB traffic blocking ratio is almost the same as with LB traffic blocking ratio. The reason is that DWFA conducts admission control to give preference to high-priority ELSPs and high-bandwidth ELSPs, which ensures that resources are used fairly between various kinds of traffic requests. We also compare the simulation results of various bandwidth granularities (i.e., two kinds-HB and LB) under various routing schemes in Fig. 8(b). We observe that our proposed DWFA gets the best performance of traffic blocking fairness for various granularity traffic requests, EFR secondly and OFR finally. The results in Fig. 8 indicate that DWFA with appropriate admission control strategy performs better in terms of blocking fairness for various bandwidth traffic requests than those algorithms without admission control.

Fig. 9 shows the performance simulation results of average logical hop counts (as defined in [2]) for different kinds of connections. Fig. 9(a) shows the simulation results of DWFA under various kinds of $R(s,d,t,b)$. From the Fig. 9(a), we can find that HP traffic travel less average logical hop counts than LP traffic, which means that smaller number of o-e-o conversions is needed and leads to lower end-to-end delay and jitter. The reason lies in our employed QoS-aware adaptive routing strategies, such that HP requests will get lower logical hop counts than

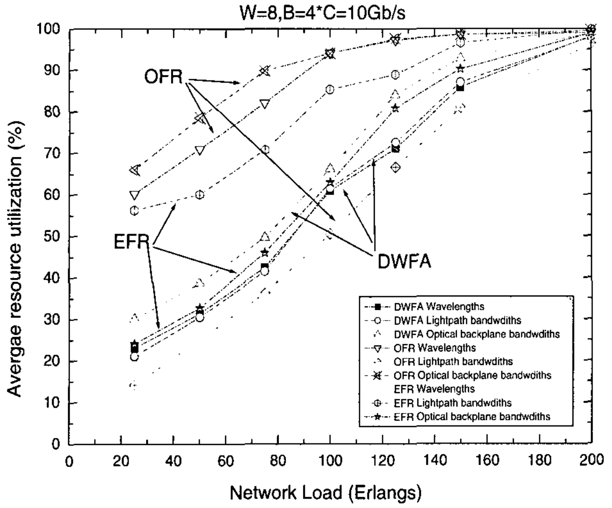


Fig. 10. Performance simulation results of resource utilization for various routing scheme.

LP requests. We also compare the simulation results of traffic average logical hop counts under various routing schemes in Fig. 9(b). We can find that when network load becomes greater than approximately 100 Erlangs, DWFA outperforms OFR and EFR schemes. But under a lower network load, OFR performs the best. This is because under lighter network load, OFR can easily setup single-hop lightpaths for each kinds of traffic request. But under higher network load, it becomes difficult to setup single-hop lightpaths. The results in Fig. 9(b) indicate that DWFA performs better under high network load in terms of traffic average logical hop counts, which helps to improve network throughput and traffic QoS performance metrics.

We finally show the simulation results of network resource utilization including wavelength utilization (optical-layer resource utilization, which is defined as the number of used wavelengths over the total number of wavelengths), lightpath utilization (electrical-layer resource utilization, which is defined as the used bandwidth of lightpaths over the total bandwidth of lightpaths), and optical backplane bandwidth usage (grooming resource usage, which is defined as the used bandwidth of optical backplane over the total bandwidth of optical backplane) under various routing schemes in Fig. 10. It is straightforward to see that, under the same network load, OFR scheme will exhaust optical backplane bandwidth/wavelength more quickly than other routing schemes. Because OFR scheme always prefers to setup single-hop lightpaths for any kind of new requests, while the established lightpaths utilization still remains lower. EFR is contrary to OFR. We can also find that DWFA always has better load balancing (tradeoff) between three kinds of resource than OFR and EFR, which simultaneously helps to improve the performance of traffic blocking ratio. So we can say that the proposed adaptive DWFA scheme can achieve global efficiency in resource utilization, which will help to implement advanced traffic engineering in the next generation optical Internet.

VI. CONCLUSION

The topic of online integrated routing/provisioning in GMPLS-based multi-service multi-granularity optical Internet is becoming very important for service providers. In this paper, we develop an adaptive differentiated integrated routing scheme called DWFA, which consists of a simplified weighted graph model, a service/bandwidth differentiation mechanism and an adaptive routing strategy. The proposed scheme retains the benefits of optical bypassing for high priority/bandwidth traffic requests; at the same time, it also provides electrical grooming for low priority/bandwidth traffic requests. We show by simulation results that the DWFA, a fairly comprehensive routing scheme, performs better than overlay routing schemes in terms of performance metrics such as traffic blocking·ratio and global efficiency in resource utilization. In addition, the proposed scheme remains easy of design and implementation for service providers.

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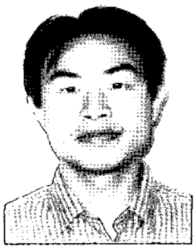

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