A backup path wavelength rearrangement scheme in an all optical network

Rose Q. Hu, Weiwei Hu, Georgios Lazarou
*Department of Electrical and Computer Engineering
Mississippi State University
Mississippi State, MS 39762-9571, USA
Email: hu@ece.msstate.edu

Abstract — **In this paper, we propose a backup path wavelength reassignment scheme that greatly improves the connection blocking probability in an all-optical network without interrupting the service of ongoing traffic flows. The unique feature of our scheme is that it performs wavelength retuning on the backup paths to improve the acceptance probability of new connection requests. We showed through simulation experiments that the proposed scheme reduces the connection blocking probability by 15% to 40% when compared with the schemes without wavelength rearrangement. In addition, we showed that the combination of backup path wavelength rearrangement and traffic grooming could further improve the network performance.**

Index terms – all-optical, backup path wavelength reassignment (BPWR), link-disjoint, switch-to-available-wavelength (STAW), exchange-wavelength (ECW), wavelength continuity, traffic grooming

I. INTRODUCTION

All optical networks that employ dense wavelength division multiplexing (DWDM) provide an enormous bandwidth for the future applications. The deployment of such networks can further accelerate the explosion of data traffic. With DWDM, a single fiber can carry 160 wavelengths at 10 Gbps/wavelength [1]. Hence, a fiber cut or link failure can result in a loss of an immense volume of data. Such a loss of data can have major public relations, financial, and legal consequences.

Mesh restoration schemes can quickly reroute traffic around a failure point via an alternate path [8][14][16]. Usually, such fault-tolerant schemes reserve resources on two different paths, active and backup paths, for each accepted connection. The active path carries traffic under normal operations, while the backup path provides the alternate path to be used in case of a failure.

Currently, in all optical mesh networks, full wavelength conversion is not feasible. Thus, all paths must consist with the same wavelength through all links in the path. We refer to this as wavelength continuity constraint [2][3]. Wavelength conversion at each node can deal with the wavelength continuity constraint but the technical difficulty and expense for implementation is too high [3][4].

In order to alleviate the wavelength continuity constraint in an all-optical network, lots of wavelength retuning and path rerouting techniques for WDM networks have been proposed in the literature [2][6][7][15][16]. Most of the approaches allow the rerouting of active paths, which causes service disruption of active connections. That is, in the attempt of finding paths due to a new connection request, existing active paths might get rerouted to different paths. Although the rerouting of existing active paths can enable the acceptance of new connection requests, it can cause major network service disruptions with unpredictable consequences. However, our proposed scheme does not cause such service disruptions; this is accomplished by using backup path rearrangement only.

In this paper, we propose a backup path wavelength reassignment (BPWR) scheme that improves the connection blocking probability in an all-optical network. The main objectives in designing our scheme are to (1) provide any single link failure protection for the network (2) maximize the number of successfully established paths while guaranteeing absolutely no service disruptions, and (3) minimize the impact of wavelength continuity constraint on connection blocking probability. In addition, we show that the combination of our scheme with traffic grooming can further decrease the connection blocking probability.

The rest of the paper is organized as follows. In Section II, we present the problem statement and address the system notations and constraints. Section III provides a short discussion on wavelength routing, and Section IV discusses the wavelength assignment scheme with traffic grooming. Section V presents the proposed backup path wavelength reassignment scheme. Section VI presents the performance evaluation, and the paper concludes with Section VII.

II. PROBLEM STATEMENT AND CONSTRAINTS

A. Problem statement

An all-optical mesh network is modeled by a weighted, directed graph $G(V, E, C, \Lambda)$, where N is the set of nodes, E is the set of unidirectional links, C is the cost function for each link, and Λ represents the set of wavelengths that can be multiplexed on each optical fiber.

Connection requests arrive at the network randomly, usually following a Poisson process with the connection holding time exponentially distributed. The connection is accepted by the bandwidth availability on each fiber-link. Furthermore, wavelength continuity constraint should be considered when deciding the wavelength availability in the all-optical networks, where it is assumed that there is no wavelength converter available and an accepted connection should traverse on the same wavelength from source to destination.

Recent mesh restoration research studies [10][11] proposed the concept of SRLG (Shared Risk Group Link). A SRLG is defined as a common single-failure risk shared by a set of paths. Two paths are said to be SRLG-disjoint if they do not share any SRLG. An active path and its backup path must be SRLG-disjoint so that the network can restore from any single failure. The capacity allocated on the backup path, on the other hand, can share with other backup paths if their active paths are SRLG-disjoint. In this paper the single-failure risk by default is defined as single-link failure. Two paths are said to be SRLG-disjoint if they do not share any links.

When a connection request enters such a network, two link-disjoint routes should be searched: one for active path and one for backup path. The wavelength continuity constraint further restricts a single connection to be routed through a set of links with the same wavelength from source to destination. A connection is rejected when no free continuous wavelength is available either on active path, or on backup path, or on both. A single connection can occupy a portion bandwidth of a wavelength. Thus wavelength sharing among multiple connections is possible.

In this paper, a Backup Path Wavelength Reassignment (BPWR) scheme is proposed. BPWR rearranges the backup path wavelengths of the existing connections so that the chance of accepting the new connection is increased. The algorithm consists of the following three steps.

1. Wavelength routing: When a connection request arrives at the network, the source node is responsible for computing two best link-disjoint paths: one for active path and one for backup path.
2. Wavelength assignment: First-fit wavelength assignment method [13] is employed to assign a continuous wavelength to both active and backup paths for the coming connection.
3. Wavelength reassignment: If wavelength assignment in 2 fails, BPWR is activated to perform wavelength rearrangement on the existing backup paths. There are two wavelength rearrangement schemes: Shift-To-Available -Wavelength BPWR (STAW-BPWR) shifts an existing backup path to a new free wavelength; Exchange-Wavelength BPWR (ECW-BPWR) exchanges wavelength assignments between two existing backup paths.

B. Notations

The notations used in this papr are as follows:

p_a^i	active path for request *i*;
$p_a^i(l)$	the *lth* link of path p_a^i
p_b^i	backup path for request *i*;
$p_b^i(l)$	the *lth* link of path p_b^i
l_a^i	the set of links traversing route p_a^i; i.e., $l_a^i = \bigcup_m p_a^i(m)$
l_b^i	the set of link traversing route p_b^i; i.e., $l_a^i = \bigcup_m p_a^i(m)$
ω	number of total wavelengths on each link
λ_k	wavelength *k, k=1, 2, …., ω ;*
$C_a^i(l, \lambda_k)$	cost for using wavelength λ_k on link *l* of path p_a^i
$C_b^i(l, \lambda_k)$	cost for using wavelength λ_k on link *l* of path p_b^i

$$C_a^i(\lambda_k) = \sum_l C_a^i(l, \lambda_k)$$ total cost for using wavelength λ_k on path p_a^i

$$C_b^i(\lambda_k) = \sum_l C_b^i(l, \lambda_k)$$ total cost for using wavelength λ_k on path p_b^i

C. Constraints

The list of networking constraints used in the formulation is as follows.

1. Wavelength sharing among multiple connections is allowable, i.e., traffic grooming is allowable.
2. A single wavelength either carries active paths, or backup paths, but not both.
3. p_a^i and p_b^i must be linking disjoint.
4. p_a^i and $p_a^j (i \neq j)$ can share the same wavelength on a link only if the wavelength has enough bandwidth to accommodate both connections.
5. p_b^i and $p_b^j (i \neq j)$ can share the same wavelength on a link if their active paths p_a^i and p_a^j are link disjoint, or if the wavelength has enough bandwidth to accommodate both connections.
6. Wavelength continuity constraint must be satisfied.

III. Wavelength Routing

When a connection request arrives at the network, the source node is responsible for computing two best link-disjoint paths: one for active path and one for backup path. In [8], *K*-shortest path algorithm is used for minimum joint-path cost selection. The algorithm computes *K* active paths based on Dijakstra's shortest path algorithm. For each active path, a link-disjoint backup path is selected. Finally a pair of active and backup paths with minimum number of joint-path hops is denoted as the best choice. The active path is p_a^i and the backup is p_b^i.

IV. Wavelength Assignment

In this paper, wavelength sharing among multiple connections, i.e., traffic grooming, is allowable. As pointed in [19][20][20], traffic grooming makes the wavelength assignment and mesh restoration problem more challenging. Without traffic grooming, a wavelength can only be utilized by only one connection even though it has more room to accommodate additional traffic. In this paper, the following wavelength assignment algorithm with traffic grooming capability is developed. The algorithm can be easily scaled down for non-traffic grooming scenario by assuming each connection asks for one wavelength bandwidth.

For each <wavelength *k*, link *n*> pair in the network, an array *R[a,k,n], a=1,2,.., M, k=1,…,ω, n=1,…,N,* is maintained to record the bandwidth that has been soft-reserved by the existing backup paths for *ath* SRLG group. *M* is the total number of SRLG groups defined in the network. Here *n* is a global link index and *N* is the total number of links in the network. We also maintain a local link index, *l*, for each path. For example, for wavelength-link pair <2,3>, *R[2,2,3]* represents the amount of bandwidth required on wavelength λ_2 of link 3 to restore SRLG 2 failure for the current network traffic. Since we assume single link failure restoration, the total soft-reserved backup capacity *R[k,n]* on each <wavelength *k*, link *n*> pair in the network should be calculated as the maximum over all SRLG groups, i.e., $R[k,n] = \max_{a=1}^{M} R[a,k,n]$.

The active path wavelength assignment is simple. It takes the first fit wavelength along the active path. Assume the flow request asks for *x* amount of bandwidth. The algorithm searches among ω wavelengths on each link along the active path p_a^i. The first fit wavelength that has *x* amount of free capacity on each link of p_a^i is selected.

Given the above notations and definitions, the backup path wavelength assignment algorithm works as follows:

- Initially, define all SRLG groups for the given networks. For single link failure restoration, each individual link represents a SRLG group. Thus a flow whose active path traversing 5 links will belong to 5 different SRLG groups. Any link-disjoint paths are SRLG-disjoint. Obviously *M* = the number of links in the network. Initially *R[a,k,n] = 0,* $\forall$ *a, k,n.*
- Identify the SRLG groups to which a new flow request *i* belongs. Denote this set as $\psi(i)$.
- If there exists a wavelength *k* that has enough bandwidth, i.e., *R[a,k,n]* + *x* ≤ single wavelength

bandwidth, $\forall a \in \psi(i)$, , $\forall\ p_b^i(n) \in l_b^i$, wavelength k is assigned to the new flow. If there are ties, the first fit will be selected.

- When a new flow is accepted, it updates the reservation array on wavelength k for each link n on the backup path in the following way: $R[a,k,n] = R[a,k,n] + x$, $\forall a \in \psi(i)$, $\forall\ p_b^i(n) \in l_b^i$.
- If inadequate capacity is available to support the new flow request, backup wavelength reassignment for the existing flows is proposed as follows.

V. BACKUP PATH WAVELENGTH REASSIGNMENT (BPWR)

Backup path wavelength rearrangement will not have any impacts on the active flows so that no service interruption is introduced. Backup path rearrangement can be achieved by either moving the existing backup paths to other routes, or reassigning wavelengths to the path but maintaining its route. In this paper, we will concentrate on wavelength reassignment for backup paths with no path rerouting. In order to perform backup path wavelength reassignment, two wavelength-retuning methods are introduced.

1. Switch-to-Available-Wavelength (STAW): STAW retunes an existing backup path to a free wavelength.
2. Exchange-Wavelength (ECW): ECW exchanges the wavelength assignment between two existing backup paths.

A. STAW-BPWR

In order to illustrate the algorithm, we use a simple 5-node 8 bi-directional link mesh network as an example. Assume each link carries 3 different wavelengths: λ_1, λ_2, λ_3. We use this network as an example to show how STAW-BPWR works. For simplicity, no traffic grooming is assumed in this example.

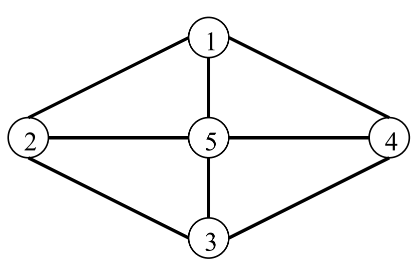

Figure 1. 5-node 8-link example Network

For each connection coming into this network, it has a <source node, destination node> id. The connections in progress are <1, 3>, <1, 5>, <2, 5>, <4, 3>, and <2, 4>. The route and wavelength assignment for each connection is given in Table 1, where AP stands for active path and BP stands for backup path.

Connection	AP: wavelength	BP: wavelength
<1, 3>	1-5-3: $\lambda 1$	1-4-3: $\lambda 2$
<1, 5>	1-5: $\lambda 2$	1-2-5: $\lambda 2$
<2, 5>	2-5: $\lambda 1$	2-1-5: $\lambda 3$
<4, 3>	4-3: $\lambda 1$	4-5-3: $\lambda 3$
<2, 4>	2-1-4: $\lambda 1$	2-3-4: $\lambda 3$

Table 1. Wavelength allocation for the sample network

There is a corresponding network subgraph for each wavelength. In each wavelength specific subgraph, links taken by active paths are marked in red; links taken by backup paths are marked in dotted blue lines. Dotted Black lines represent vacant links.

Assume a new connection request <2, 3> comes into the network. The only route with a continuous free wavelength available is route 2-3 on wavelength λ_1. The coming request has to be rejected if no wavelength reassignment is conducted. However, if backup path 4-5-3 on λ_3 for connection <4, 3> is retuned to wavelength λ_2, λ_3 will be released on links 4-5 and 5-3. Thus route 2-5-3 on wavelength λ_3 and route 2-3 on wavelength λ_1 are selected as the two link-disjoint paths for the new connection request. Figure 2 compares the network subgraphs before and after STAW algorithm for 3 wavelengths, respectively.

B. ECW-BPWR

ECW-BPWR swaps the wavelength assignments between two existing backup paths, which share their paths on some common links. In order to illustrate the algorithm, the same example network is used. The connections in progress are <1, 2>, <1, 3>, <1, 5>, <4, 5>, and <2, 5>. The route and wavelength assignment for each connection is given in Table 2. For simplicity, no traffic grooming is assumed in this example.

A new connection request <2, 3> comes into the network. From Figure 3, the only route with a free continuous wavelength for the coming connection is route 2-3 on wavelength λ_2. If there is no backup path rearrangement, the new request has to be rejected. With ECW-BPWR, backup path 1-4-3 on wavelength λ_2 can exchange its wavelength with backup path 4-3-5 on λ_3 so that wavelength λ_3 is released on link 5-3. Thus route 2-5-3 on wavelength λ_3 is assigned as the backup path.

Since routes 2-3 on λ_2 and 2-5-3 on λ_3 are two link-disjoint paths, the new connection <2, 3> is accepted. Figure 3 compares the network subgraphs before and after STAW algorithm for 3 wavelengths, respectively.

Connection	AP: Wavelength	BP: Wavelength
<1, 2>	1-2: $\lambda 1$	2-3-4-1: $\lambda 1$
<1, 3>	1-5-3: $\lambda 1$	1-4-3: $\lambda 2$
<1, 5>	1-5: $\lambda 2$	1-2-5: $\lambda 2$
<4, 5>	4-5: $\lambda 1$	4-3-5: $\lambda 3$
<2, 5>	2-5: $\lambda 1$	2-1-5: $\lambda 3$

Table 2. Wavelength allocation for the sample network

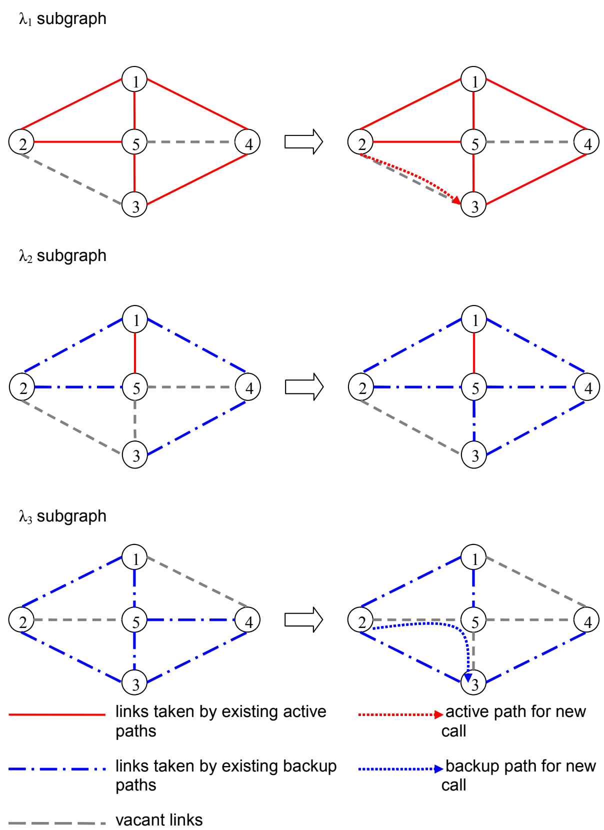

Figure 2. Wavelength subgraphs before and After STAW-BPWR

C. BPWR algorithm formulation

In this section, the general BPWR algorithm is formulated. For each new connection *i*, a pair of link-disjoint paths, p_a^i and p_b^i, can be selected. BPWR algorithm is activated when:

1) A continuous wavelength is available on the active path p_a^i but not on the backup path p_b^i.
2) A continuous wavelength is available on the backup path p_b^i but not on the active path p_a^i.
3) No continuous wavelength is available on either the active path p_a^i or the backup path p_b^i.

BPWR algorithm works in slightly different ways under three scenarios.

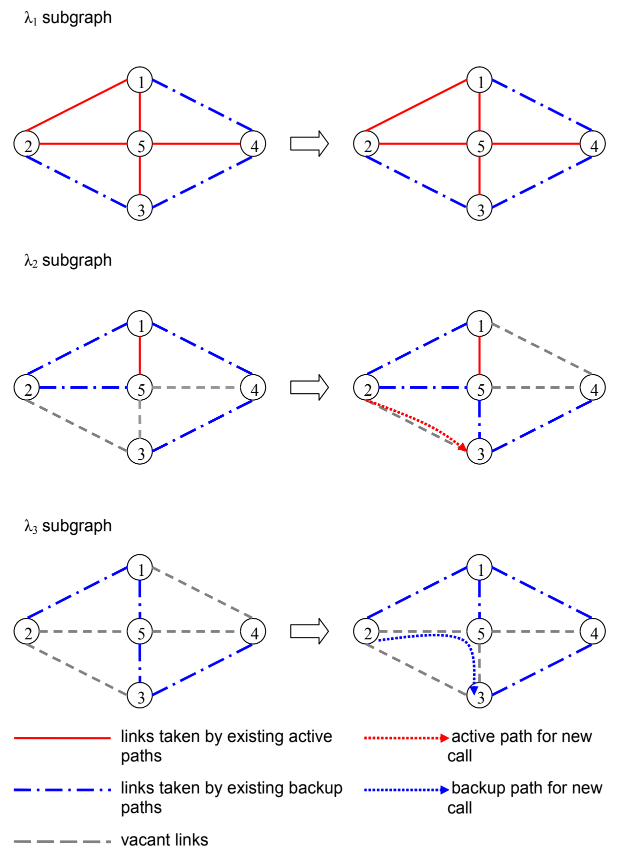

Figure 3. Wavelength subgraphs before and after EXW-BPWR

D. Scenario 1 BPWR

Scenario 1 BPWR aims to find a continuous wavelength for p_b^i via wavelength reassignment

1. Wavelength-link cost function

The *kth* wavelength on $p_b^i(l)$, $k=1,..,\omega$, $p_b^i(l) \in l_b^i$, can be categorized into four types:

1) Wavelength that is free;

2) Wavelength taken by any backup path p_b^j, whose active path p_a^j is link-disjoint with p_a^i (represented by $p_a^j \varnothing p_a^i$);
3) Wavelength taken by any backup path p_b^j, whose active path p_a^j is not link-disjoint with p_a^i (represented by $p_a^j \cap p_a^i$).
4) Wavelength taken by any active path.

The wavelength-link cost function $C_b^i(l,\lambda_k)$ for using wavelength λ_k on the *lth* link of p_b^i is defined as follows:

$$C_b^i(l,\lambda_k) = \begin{cases} 0 & \text{if } \lambda_k \text{ is a type 1 or type 2 wavelength} \\ \varepsilon & \text{if } \lambda_k \text{ is a type 3 wavelength} \\ +\infty & \text{if } \lambda_k \text{ is a type 4 wavelength} \end{cases}$$

If the total backup path cost $C_b^i(\lambda_k) = \sum_l C_b^i(l,\lambda_k) = 0$, λ_k is available for p_b^i and no BPWR algorithm is needed. If $C_b^i(\lambda_k) = \infty$ for all wavelengths, i.e., $k=1,..,\omega$, the new connection will be rejected and no BPWR algorithm is needed. If $0 < C_b^i(\lambda_k) < \infty$ for at least one wavelength λ_k and no other wavelength makes the backup path cost at 0, the following BPWR algorithm is activated.

2. BPWR Algorithm

The BPWR procedures for scenarios 1 are as follows:

Step 1) Convert the given physical network to ω per-wavelength based subgraphs.

Setp 2). Perform wavelength reassignment:

```
While (k<=ω)
    If 0 < C_b^i(λ_k) < ∞
        Call BPWR() procedure.
        If BPWR() completes
        successfully
            k=ω+1;
        else
            k++;
    Else
        k++;
    Endif
End While
```

Step 3). If BPWR completes successfully, the new connection i is accepted. Otherwise, connection i is rejected.

Procedure BPWR()

1) Since $0 < C_b^i(\lambda_k) < \infty$, wavelength λ_k along path p_b^i has been taken by some existing backup paths. Let $l_b^i(\lambda_k)$ denote the subset of l_b^i on which wavelength λ_k has been taken. $l_b^i(\lambda_k) \subseteq l_b^i$.

2) **For** each link $p_b^i(l) \in l_b^i(\lambda_k)$

Let p_b^j represent the back up path(s) that have taken wavelength λ_k on link $p_b^i(l)$. The purpose of BPWR is to retune p_b^j to other wavelengths so that λ_k can be released to accommodate connection *i*.

Let $C_b^j(\lambda_d) = \sum_m C_b^j(m,\lambda_d)$ be the path cost for retuning p_b^j from λ_k to λ_d, $d \neq k$.

```
While (d<= ω)
    If C_b^j(λ_d) = 0   //Activate STAW
        p_b^j can be retuned to wavelength λ_d. λ_k
        can be released on link p_b^i(l) .
        STAW succeeds on link p_b^i(l) .
        d= ω+1
    Else
        d++
End While

If STAW fails on link p_b^i(l)
 While (d<= ω)
    If C_b^j(λ_d) < ∞   //activate ECW
        Call ECW().
        if ECW() succeeds on p_b^i(l)
            d= ω+1
        else
            d++;
    End If
 End While
End If

If both STAW and ECW fail on link p_b^i(l) ,
    BPWR fails. Exit BPWR()
Else
    l++; //Go to the next link in l_b^i(λ_k)
End If
End For loop on l.
```

3) Compute $C_b^i(\lambda_k)$ for path p_b^i. If $C_b^i(\lambda_k) = 0$ BPWR() completes successfully. Otherwise, BPWR() fails.

End BPWR()

Procedure ECW ():

1) Since $0 < C_b^j(\lambda_d) < \infty$, wavelength λ_d along path p_b^j has already been used by some other existing backup paths. Let $l_b^j(\lambda_d)$ denote the subset of l_b^j on which wavelength λ_d has been taken. $l_b^j(\lambda_d) \subseteq l_b^j$.

2) **For** each link $p_b^j(ll) \in l_b^j(\lambda_d)$.

   Let p_b^h represent the back up path(s) that have taken wavelength λ_d on link $p_b^j(ll)$. The purpose of ECW is to exchange wavelength λ_d of p_b^h with wavelength λ_k of p_b^j if possible so that λ_k can be released on link $p_b^i(l)$. Notice that p_b^h and p_b^i must be link-disjoint. Otherwise retuning p_b^h to λ_k will take away λ_k on some other links along p_b^i.

   Calculate the cost of p_b^h if p_b^h is retuned to wavelength λ_k.

   If p_b^h and p_b^i are link-disjoint,

   If $C_b^h(\lambda_k) = \sum_{m \neq p_b^j(ll)} C_b^h(m, \lambda_k) = 0$

   p_b^h can be retuned from wavelength λ_d to λ_k so that λ_d is released on link $p_b^j(ll)$. ll++.

   Else

   ECW() fails. Exit ECW().

   End if

   Else

   ECW() fails. Exit ECW().

   End For

3) Compute the path cost for p_b^j on λ_d.

   if $C_b^j(\lambda_d) = 0$,

   ECW() completes successfully.

   else

   ECW() fails.

End ECW()

Since traffic grooming is allowable, multiple backup paths traversing the same wavelength-link will be retuned one by one to its new wavelength in both STAW and ECW. The complexity of the algorithm can be reduced by retuning these multiple backup paths together to the same new wavelength at the cost of much higher BPWR failure rate.

E. Scenario 2 BPWR

Scenario 2 BPWR aims to find a continuous wavelength for p_a^i via wavelength reassignment. Similarly, the *kth* wavelength on $p_a^i(l)$, $k=1,..,\omega$, $p_a^i(l) \in l_a^i$, can be categorized into three types:

1. Wavelength that is vacant;
2. Wavelength taken by other backup paths;
3. Wavelength taken by other active paths.

The wavelength-link cost function $C_a^i(l, \lambda_k)$ for using wavelength λ_k on the *lth* link of p_a^i is defined as follows:

$$C_a^i(l, \lambda_k) = \begin{cases} 0 & \text{if } \lambda_k \text{ is a type1 wavelength} \\ \varepsilon & \text{if } \lambda_k \text{ is a type2 wavelength} \\ +\infty & \text{if } \lambda_k \text{ is a type3 wavelength} \end{cases}$$

If the total active path cost $C_a^i(\lambda_k) = \sum_l C^i(l, \lambda_k)$ is 0, λ_k can be assigned to the active path of the new connection. The new connection is accepted without BWPR. If $C_a^i(\lambda_k) = \infty$ for all wavelengths $k=1,..,\omega$, the new connection is rejected. If $0 < C_b^i(\lambda_k) < \infty$ for at least one wavelength k and no other wavelength makes the active path cost at 0, BWPR algorithm is then activated. Since wavelength reassignment only happens to the backup paths, BPWR algorithm works exactly the way as that in scenario 1.

F. Scenario 3 BWPR

Scenario 3 BPWR can be achieved by the combination of the previous two scenarios. Scenario 2 BPWR algorithm is first activated to search for the active path wavelength. Scenario 1 BPWR is followed to search for backup path wavelength. If both scenario 2 and scenario 1 BPWR proedures succeed, scenario 3 BPWR succeeds. If either scenario 1 or scenario 2 BPWR fails, scenario 3 BPWR fails.

VI. PERFORMANCE RESULTS

A. Performance modeling

In this section, the performance evaluation on the proposed algorithm is presented. The numerical results are generated based on the 14-node 18-bidirectional-link NSFNET, as shown in Figure 4. Each link consists of 5 wavelengths. Each wavelength represents an OC-48 link. The simulation is conducted in ns-2.

For every pair of the source and destination, 3 shortest link-disjoint route pairs are pre-computed off-line. We simulate a dynamic network environment in which the connection requests arrive at edge nodes according to Poisson process and the connection holding time follows an exponential distribution. Among all 14 nodes, six evenly scattered nodes are selected as edge nodes. The connection requests are uniformly generated from each of 6 edge nodes and distributed to the other 5 edge nodes with equal probability. Other 8 nodes serve only as intermediate nodes. Average connection-holding time is normalized to 1. The arrival rate per edge node is provided as number of connection requests/unit time. The connection arrival rate changes in the simulation in order to achieve different traffic load. Each wavelength is equivalent to an OC-48 bandwidth. The bandwidth demand of a coming connection can be any one of the following values with equal probability: OC-48, OC-24, and OC-12. With traffic grooming, a wavelength can be shared among multiple connections. Without traffic grooming, each connection will be assigned an entire wavelength regardless of its actual bandwidth demand. The performance evaluation will focus on presenting the connection blocking probability as a function of the connection arrival rate for different case studies.

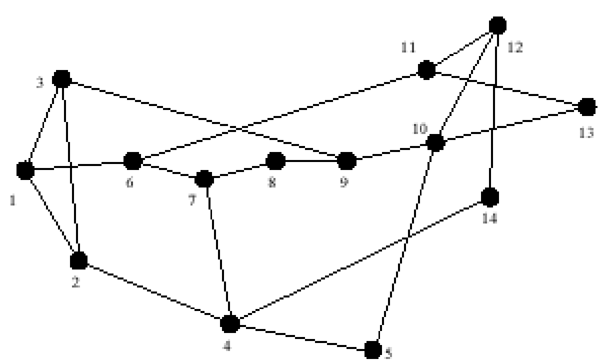

Figure 4. A 14-node NSNFET mesh network

B. Simulation results

During the simulations, each new request will search for two link-disjoint paths. Traffic grooming is allowed. All the simulation results are generated based on these conditions, unless specified otherwise.

In Figure 5, the connection blocking probability versus per node connection arrival rate is plotted. The red line represents the blocking probability without BPWR; the black line represents the blocking probability with BPWR. Both cases are compared against the ideal blocking probability, which is generated assuming that full wavelength conversion is implemented. Backup path wavelength reassignment significantly reduces the blocking probability by 15 ~ 40% under different arrival rates. As we expected, both red line and black line have much higher blocking rate than with full wavelength conversion, which provides the lower bound study on the blocking probability. We can see that BPWR greatly alleviates the wavelength continuity constraint although it does not completely compensate for the limitation. Figure 6 gives the corresponding computation time overhead caused by BPWR. Since BPWR only deals with backup path rearrangement, the computation time for BPWR is not as critical as for wavelength retuning on active paths. The overhead time only has impact on the network computation power and connection setup time. Simulation results show that in average BPWR causes about 8% additional computation time. The computation overhead does not increase with the traffic load. It will increase when the network increases.

The study in this paper focuses itself on link-disjoint protection. But the BPWR concept can be easily expanded to path-disjoint protection, in which each connection will search for two path-disjoint routes. The corresponding BPWR scheme remains almost the same. The BPWR performance comparison between link-disjoint protection and path-disjoint protection is provided in Figure 7. As we expected, path-disjoint protection introduces slightly higher connection blocking probability than link-disjoint protection. BPWR brings in similar improvement on blocking probability for path-disjoint protection as for link-disjoint protection. BPWR algorithm efficiently enhances the network performance by increasing the throughput in the network.

Traffic grooming is supported in the results presented in Figure 5 to Figure 7. Without traffic grooming, the incoming traffic will experience higher blocking probability. Figure 8 compares the blocking probability among 4 cases: with/without traffic grooming + with/without BPWR. All the curves are generated by using link-disjoint protection. The results demonstrate that the traffic grooming can greatly improve the connection blocking probability. When the traffic load is rather low, the significance of traffic grooming is not prominent since the network bandwidth is sufficient with low traffic load. The blocking probability is reduced more and more when the traffic load gets higher and higher. Worthy of mention, the traffic grooming capability augments BPWR performance greatly since traffic grooming allows more flexibility for BPWR to search for retuning possibility. For example, without traffic grooming, BPWR reduces the blocking probability from 35% to 32.5% when the per node arrival rate is 8. The decrease is about (35%-32.5%)/35%=7%. But with traffic grooming, the blocking probability is reduced from 24% to 20% at the same arrival rate. The decrease is about (24%-20%)/24%=17%. The similar trend can be observed with other arrival rates.

VII. CONCLUSIONS

This paper proposes a backup path wavelength reassignment scheme to improve the blocking probability in an all-optical network. Compared with most existing rerouting/wavelength reassignment schemes, the proposed scheme only has to deal with backup paths and introduces zero service interruption to the traffic in the network. The BPWR scheme only brings in 8% additional computation time in average. Thus the impact on the network computation power and connection set up time is very moderate. The performance evaluation indicates that the connection blocking probability can be decreased in the range of 15-40%. The combination of BPWR and traffic grooming can efficiently alleviate the wavelength continuity constraint.

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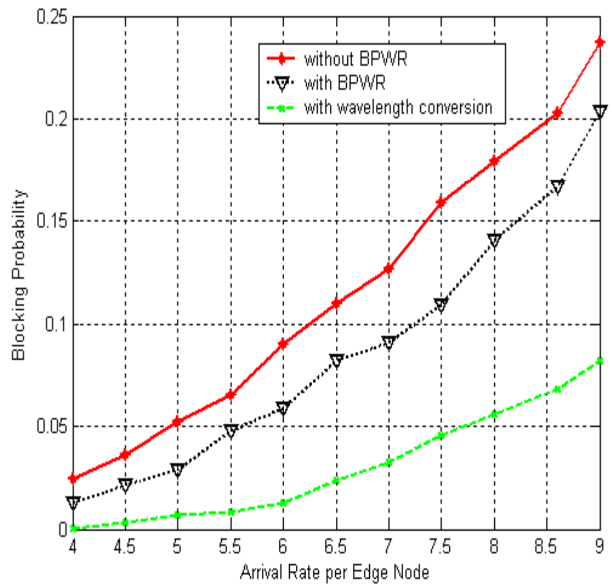

Figure 5. Blocking probability comparison: with BPWR and without BPWR

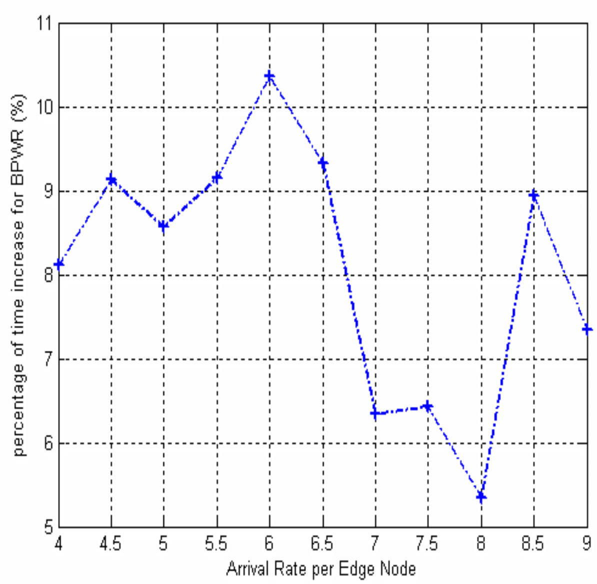

Figure 6. Computation time overhead for BPWR

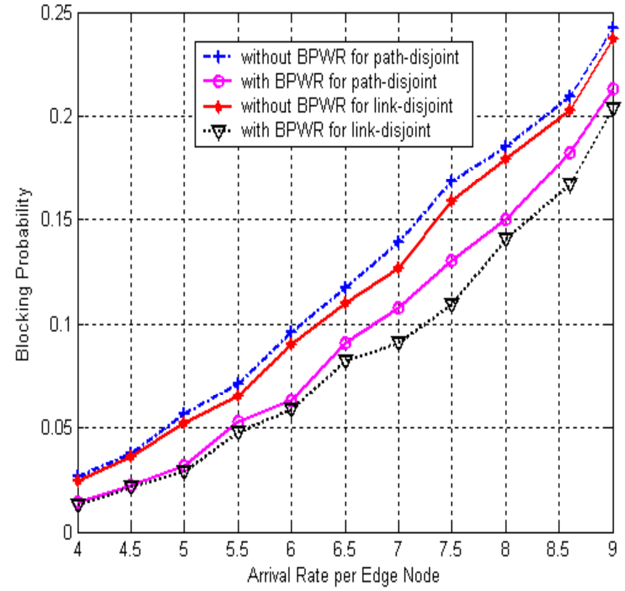

Figure 7. Blocking probability comparison: link-disjoint vs. path disjoint

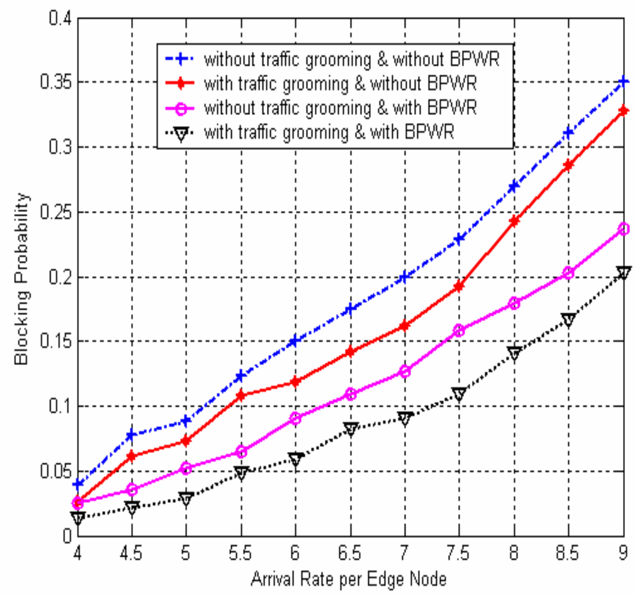

Figure 8. Blocking probability comparison: with and without traffic grooming