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Dynamic Wavelength Routing in All-Optical Mesh Networks

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***Abstract*— Wavelength-division multiplexing (WDM) offers the capability to handle the increasing demand of network traffic in a manner that takes advantage of already deployed optical fibers. Lightpaths are optical connections carried end-to-end over a wavelength on each intermediate link. Wavelengths are the main resource in WDM networks. Due to the inherent channel constraints, a dynamic control mechanism is required to efficiently utilize the resource to maximize lightpath connections.**

In this paper, we investigate a class of adaptive routing called *Dynamic Wavelength Routing* (DWR), in which wavelength converters (WCs) are not utilized in the network. The objective is to maximize the wavelength utilization and reduces the blocking probability in an arbitrary network. This approach contains two sub-algorithms: *Least Congestion with Least Nodal-degree Routing algorithm* (LCLNR) and *Dynamic Two-end Wavelength Routing algorithm* (DTWR). We demonstrate that DWR can significantly improve the blocking performance, and the results achieved as good as placing sparse WCs in the network.

I. Introduction

The relentless need and continuously increasing demand for telecommunication leads to wavelength-routed all-optical WDM networks as the broadband backbone data transport networks [1]. In WDM, the optical spectrum is divided into many non-overlapping wavelength channels. Multiple kinds of traffic are multiplexed onto a fiber by using different wavelength channels. Wavelength routers can switch the input optical signals according to their wavelengths. Lightpath is an optical channel, which is carried end-to-end optical connection from a source node to a destination node without any intermediate electronics, created by the allocation of the wavelength throughout each intermediate link [2] [3]. Thus, lightpath is a direct communication path' between any two nodes. If no wavelength conversion is available in networks, lightpath must use the *same* wavelength on all the links along its path from the source to the destination edge node. In Figure 1, for example, if a call request on a route 1-2-4-6 is assigned wavelength λ_1 to establish a lightpath, then the links 1-2, 2-4 and 4-6 need to have λ_1 free to support this connection. This restriction is called the *wavelength continuity constraint*.

Wavelength continuity constraint can lead to the inefficient utilization of wavelength channels and high blocking probability. Thus, the task of efficient utilization of wavelengths in optical networks becomes an important issue.

An idea that employs wavelength converters (WCs) in all-optical WDM networks to increase wavelength utilization has been proposed [4] [5] [6]. The wavelength continuity constraint is removed, thus reducing network blocking. WCs, however, are costly devices. It is not cost-efficient to set up WC at each routing node. Therefore, one possible scheme to address this issue is to set up a sparse number of WCs at some specific selected nodes to achieve adequate cost-effective performance [7]. Alternatively, call requests need to be assigned appropriate routes and wavelengths over the lightpaths to maximize throughput of traffic pattern. This consideration is known as the *routing and wavelength assignment* (RWA) problem [8] [9].

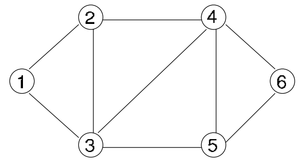


Fig. 1. A 6 nodes and 9 links topology

The study of RWA algorithms is based on traffic load assumptions. If the traffic patterns in the network are organized in advance, the traffic variations can be formulated as a mixed-integer linear program (MILP) to yield an optimum solution [10]. However, with dynamic traffic, each lightpath request between source and destination *(s-d)* pair arrives at random, and has a random holding time; after which it is tore down and the resources are set free. The objective in the dynamic traffic case is to efficiently select routes and assign wavelengths to connections in the network at any time so as to minimize the connection blocking, or maximize the number of call connections. Both static and dynamic traffic problems are NP-complete [10].

RWA problem can be decoupled into the routing sub-problem and the wavelength assignment sub-problem. Among proposed wavelength assignment algorithms, the first-fit assignment (FF) [11] is the most popular and easy to implement algorithm. This algorithm selects wavelength according to an ascending order from the available wavelengths along the path. In general, the first-fit assignment achieves a lower call blocking probability than the random assignment especially when the number of wavelength channels per link is small.

Routing strategy can be classified into two types: fixed and adaptive. In fixed routing, the routing path between any two end-nodes is pre-defined. The candidate path number can be one or more. Normally, paths are chosen for the shortest paths or the minimum cost paths. Adaptive routing determines routes after considering the current network state when a connection request arrives. This sort of routing is more efficient than the fixed routing. Thus, recent studies on routing strategies mostly focus on adaptive routing [12]. One of the earliest proposed adaptive routing strategies is Least Loaded Routing (LLR) [5]. LLR chooses the least congested path and assigns a wavelength among the available wavelengths over a set of *k* shortest paths. However, LLR may introduce a longer route, thus wasting the network resources and resulting in a higher blocking rate.

In [13], Hsu *et al.* propose a weighted-shortest path strategy (WSP) to select a route. Their objective is to minimize the network resource cost and balance the traffic load among each link as much as possible. Their analytical model, however, only considers that all nodes are equipped with a full-range of wavelength converters. Chu *et al.* proposed a weighted least-congestion routing and first-fit wavelength assignment algorithm (WLCR) [14]. Their algorithm focuses on a route for both the distribution of free wavelengths (F) and the lengths of the routes (h) jointly. The weight function is defined as $W = F/\sqrt{h}$. Their routes are chosen from a set of routes that have been pre-computed for each *s-d* pair. Their objective is to carry more traffic while keeping the blocking probability low. Without using WCs in the networks, their algorithms perform better than the shortest path first-fit routing (SP-FF) and fixed-alternate first-fit routing (FA-FF), but close to LLR algorithm.

In this paper, we study the RWA problem in single-fiber circuit switched wavelength routing networks where the same set of wavelengths provided on each link. To our best knowledge, most proposed adaptive routing algorithms select candidate routes from a pre-computed set of alternate paths. Normally, routes are pre-computed by the edge-disjoint k-shortest paths for each *s-d* pair [4]. A route is determined by calculating their cost or weight function, which is related to their objectives. A call is blocked if none of the pre-determined candidate routes are available at the time. The purpose of pre-defined routes is to simplify the computing process of determining a route. However, a call may not have to be blocked because some other available routes may still exist in the current network state, but are out of the pre-computed routes. This may happen especially in highly dense networks. Thus, we propose an adaptive routing approach called *Dynamic Wavelength Routing algorithm* (DWR), which consists of two algorithms: *Least Congestion with Least Nodal-degree Routing algorithm* (*LCLNR*) and *Dynamic Two-end Wavelength Routing algorithm* (*DTWR*). The objective of our proposed approach is to maximize the wavelength utilization and reduce the blocking probability in the network.

The rest of this paper is organized as follows. In section II, we present the DWR algorithm. We evaluate the performance of the DWR algorithm over arbitrary mesh topologies in section III. Finally, we conclude this paper in section IV.

II. Dynamic wavelength routing

A. Assumptions

The objective of DWR is to minimize blocking probability and maximize wavelength utilization. DWR requires extensive support from the control and management protocols to continuously update the current network state information. The link state routing algorithm is considered in our study. Our analytical model is designed under the following assumptions:

- A call (connection) request of each *s-d* pair is based on a Poisson distribution with arrival rate λ. The average service holding time is exponentially distributed with mean $1/\mu$. The offered load (Erlangs) per node is $\rho = \lambda/\mu$.
- The mesh network is a set of nodes interconnected by single-fiber links. Each fiber link is bidirectional.
- No queuing of connection requests is allowed. If a connection can not be made, it is immediately discarded.
- Each node has the same array of transmitters and receivers.
- There is no multicasting. Call request is an end-to-end model.
- Each fiber link can support each wavelength in either direction.
- Each link is bidirectional, and each link has W wavelength channels.

B. Notations

To solve the routing problem, a physical topology can be modeled as a connected graph *G(N,L)*, where *N* is the set of network wavelength routing nodes and *L* is the set of network single-fiber links. The parameters of the model are functions of the nodes, wavelength converters, fiber links and the number of wavelengths in a fiber link, where

$N = \{n_i\}$	is the set of wavelength routing nodes (e.g OXCs or OADMs).
s	denotes a source node.
d	denotes a destination node.
n_s	denotes the neighbour nodes of s.
n_d	denotes the neighbour nodes of d.
$L = \{l_i\}$	is the set of optical fiber links in the network, where $i \in \{1 \dots L\}$.
l_{mn}	denotes the link between n_m and n_n, where $m, n \in \{1 \dots N\}$.
W	is number of wavelengths in a fiber link.
$K = \{K^i_{sd}\}$	is the set of *k*-shortest paths in the ascending order of hop numbers, $i \in \{1 \dots k\}; s, d \in \{1 \dots N\}, s \neq d$.
K^i_{sd}	is the i_{th} candidate lightpath from *s* to *d*.
$h_i = \lvert K^i_{sd} \rvert$	denotes the hop number at the path K^i_{sd}.
$w^{K^i_{sd}}_{\text{common}}$	denotes the set of common free wavelengths at the path K^i_{sd}.
w^i_{sd}	denotes the number of common free wavelengths at the path K^i_{sd}, where $w^i_{sd} = \lvert w^{K^i_{sd}}_{\text{common}} \rvert$.
$w^{K^i_{sd}}_x$	denotes that wavelength channel *x* is chosen at the path K^i_{sd}.
w_{mn}	is the number of available free wavelengths at l_{mn}.
w^x_{mn}	is the set of available free wavelengths at l_{mn}, where $x \in \{1 \dots W\}$.
$deg(n_i)$	is the nodal degree at node n_i. In a random mesh topology, $2 \leq deg(n_i) \leq N - 1$.
$Path_{sd}$	is the determined lightpath from *s* to *d*.

W_{mn}	is the sum of all available free wavelengths at all links between n_n and its neighbor nodes n_m, where $W_{mn} = \sum_{n}^{deg(m)} w_{mn}$.
$O(K_{sd}^i)$	is the objective function for a candidate lightpath K_{sd}^i, and the value is w_i/h_i.

C. Concepts and Algorithms

In order to achieve its objectives, the DWR algorithm contains two sub-algorithms: the Least Congestion with Least Nodal-degree Routing algorithm (LCLNR); and the Dynamic Two-end Wavelength Routing algorithm (DTWR). The second algorithm will not be envoked if a call request can be established by the first algorithm. The first-fit wavelength assignment algorithm is considered. The objective of the LCLNR algorithm is to avoid routing dynamic traffic through congested links, thus reducing the blocking probability. The k shortest paths of each *s-d* pair are computed by the modified Dijkstra shortest path algorithm [15], and are arranged in ascending order of hop numbers. When a connection request arrives, the assigning route is determined by an objective function $O(K_{sd}^i) = w/h$, which is the rate of the number of common free wavelengths w to the hop numbers h over the route, and the route with the maximum value will be selected. The intermediate nodal degree will be considered if two or more candidate routes have the same maximum value. In this case, the route with the minimum sum of the intermediate nodal degree will be selected, $min \sum_{i=n_s}^{n_d} deg(n_i)$. If the number of candidate routes with the minimum value is still more than one, the LCLNR algorithm will randomly select one route from them. The LCLNR algorithm is given in Algorithm 1.

TABLE I
CALL CONNECTION DISTRIBUTION FOR THE TOPOLOGY OF FIGURE 1

Node number	1	2	3	4	5	6
Nodal degree	2	3	4	4	3	2
No. of s	13272	13418	13354	13354	13348	13282
No. of d	13178	13372	13472	13275	13410	13293
No. of by pass	10	5788	14080	14216	4839	8
No. of Blocked	0	15	43	35	23	0

Our results show that if a call request only considers the factors *h* and *w* to avoid routing at congested links, then most blocked requests will be at nodes with higher nodal degree. Table I demonstrates the call connection distribution in a 6 nodes and 9 links topology as shown in Figure 1. The total consecutive call numbers is 80000. Each link has 16 wavelength channels. The total traffic load is 95 Erlangs. Each *s-d pair* has 5 pre-determined shortest paths. The average number of hops is 1.46. The blocking probability is 0.2238%. Table I shows that those nodes with higher nodal degrees (nodes 3 and 4) have more calls passing through them (14080 and 14216, respectively). Also, the number of blocked calls at those nodes is higher than the other nodes. We call such node a *busy* node. The lower nodal degree nodes (node 1 and 6) have lower number of calls passing through them. Moreover, the number of blocked calls at those nodes is lower. This kind of unbalanced call distribution can be re-arranged by an approach in which the

Algorithm 1 LCLNR

Require: A physical topology $G(N, L)$, and a set of K pre -determined paths, $K_{sd}^i, i = 1 \dots k$ of connection $t = (s, d)$
Ensure: $Path_{sd} = K_{sd}^i, i \in \{1 \dots k\}$
  Calculate the objective value consumed by path K_{sd}^i: $O(K_{sd}^i) = w_i/h_i$, $\forall i \in \{1 \dots k\}$
  if $O(K_{sd}^i) = 0, \forall i \in \{1 \dots k\}$ **then**
    The call request is denied; **RETURN**
  else
    $Path_{sd} = \max_{i \in \{1 \dots k\}} O(K_{sd}^i)$, $P = |Path_{sd}|$;
  end if
  if $P \geq 2$ **then**
    Calculate:$Path_{sd} = \min_{p \in \{1 \dots P\}} \sum_{n_i \in Path_{sd}} deg(n_i)$, $P = |Path_{sd}|$
    if $P \geq 2$ **then**
      randomly select a route $Path_{sd}$
    end if
  end if
  The request is accepted. Assign a wavelength $w_x^{K_{sd}^i}$ to $Path_{sd}$ using *First-fit* technique; $w_x^{K_{sd}^i} = min(w_{\text{common}}^{K_{sd}^i})$.

nodal degree of nodes is considered. For example, a call request is made from node 1 to node 4 as shown in Figure 2. Path 1-2-4 will be chosen if both paths 1-2-4 and 1-3-4 have the same objective value. The reason is that calls can avoid passing through a busy node and thus reduce the blocking probability.

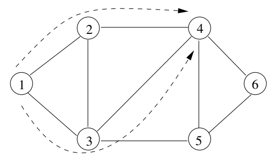


Fig. 2. Nodal degree consideration in a routing path

The objective of the second algorithm, DTWR, is to maximize the wavelength utilization. Without WC functionality in a network, call blocking is caused by the following scenarios: *Scenario A*: There are no free wavelengths available on the links between the source node and its neighbour nodes, and/or on the links between the destination node and its neighbour nodes. *Scenario B*: There are some free wavelengths available between the source node and its neighbour nodes, and also between the destination node and its neighbour nodes. However, the available wavelengths are not common at the source and destination (wavelength continuity constraint). *Scenario C*: Common free wavelength(s) can be matched at the source and destination, however, there continuous wavelengths are not available at the intermediate nodes.

WCs can only improve the blocking performance in scenarios *B* and *C*, but not in scenario *A*. The DTWR algorithm is utilized only when a call cannot be established by the LCLNR algorithm. The first step of the DTWR algorithm is to examine whether a call is going to be blocked due to the above three scenarios! If not, the second step is to remove those busy links $w_{sn_s} = 0$ and $w_{n_d d} = 0$ from *G(N,L)* and re-generate a temporary *G'(N,L')*. From *G'(N,L')*, we search for an available route from $n_s - n_d$ by the modified Dijkstra's shortest path algorithm as shown in Figure 3. Finally, we determine a proper route by the LCLNR algorithm. The DTWR is given in Algorithm 2.

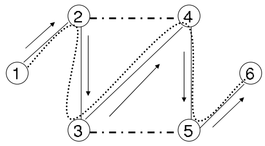


Fig. 3. Remove busy links (1-3),(4-6) and find available path from updated network state *G'(N,L')*

Algorithm 2 DTWR

Require: $|Path_{sd}| = 0$
Ensure: K^i_{sd}
  while the call request is denied **do**
    Calculate w_{sn_s}, $w_{n_d d}$, W_{sn_s}, and $W_{n_d d}$
    if $(W_{sn_s} = 0)$ or $(W_{n_d d} = 0)$ **then**
      The call request is blocked; **RETURN**
    else if $\{w^i_{sn_s}, \forall i\} \cap \{w^j_{n_d d}, \forall j\} = \emptyset$ **then**
      The call request is blocked; **RETURN**
    else
      Remove those links $w_{sn_s} = 0$ and $w_{n_d d} = 0$ on *G(N,L)*, and generate *G'(N,L')*
    end if
    Calculate a set of paths $K'^i_{n_s n_d}$ by using the modified Dijkstra's shortest path algorithm, $t' = (n_s, n_d)$
    if $|K^i_{n_s n_d}| = 0$ **then**
      $|K^i_{sd}| = 0$, the call request is blocked; **RETURN**
    else
      $K^i_{sd} \leftarrow K^i_{n_s n_d}$, Go to LCLNR
    end if
  end while

III. Numerical Results and Analysis

To evaluate the performance of our proposed routing approach, we implemented the DWR algorithm. In this section, we compare the performance of DWR, LLR and WLCR algorithms when used for the 6-node, 9-link topology (C=16,K=5), 14-node NSFNet (C=24,K=7), 19-node EON (C=24,k=7) (both topologies are shown in Figure 4), and 25-node Meshtorus topologies (C=24,k =8). Two scenarios are considered: with and without placing WCs in these networks. WCs are utilized within LLR and WLCR algorithms.

A. Performance comparison without WCs

We demonstrate the first scenario with no WCs. Figure 5(a) shows the blocking performance results for the 6-node, 9-link topology. The total traffic load is varied from 90 to 135 Erlangs, and 30,000 consecutive lightpath requests are

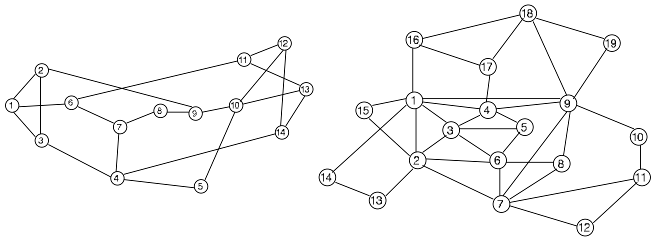
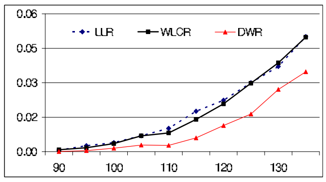
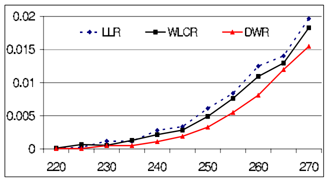


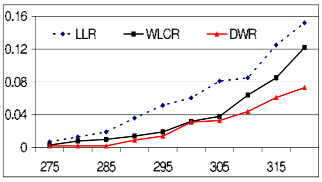
Fig. 4. 14-node NSF and 19-node EON topologies



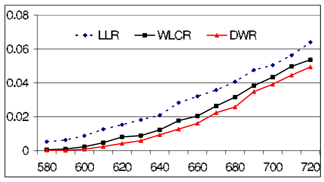
(a) The 6-node, 9-link topology



(b) NSFNet



(c) EON



(d) 5X5 Meshtorus topology

Fig. 5. Blocking performance (100%) to traffic load (Erlangs) without WCs in some topologies

generated. The DWR algorithm has $10\% - 25\%$ better blocking performance than LLR and WLCR; especially when the traffic load is high. Table II shows the call connection distribution when the DWR algorithm is used. Calls may be connected by LCLNR or DTWR algorithm; or may be blocked due to scenarios A, B or C. Table II shows that the number of connected

TABLE II

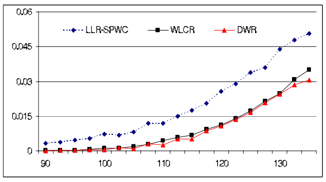
CALL CONNECTION DISTRIBUTION IN THE 6-NODE, 9-LINK TOPOLOGY

Traffic load (Erlangs)	95	105	115	125	135
Connected using LCLNR	29956	29830	29619	29238	28655
Connected using DTWR	30	84	201	270	302
Blocked: scenario A	3	6	5	14	15
Blocked: scenarios B or C	11	80	175	478	1028

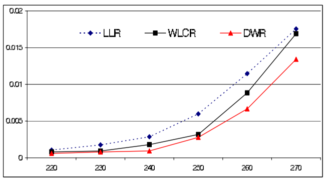
calls by the LCLNR algorithm is slightly decreased when the traffic load is increased. On the other hand, the number of connected calls by the DTWR algorithm is increased with higher traffic load. This indicates that if a routing algorithm only considers those pre-computed routes, it may miss some feasible routes which are out of their pre-determined routes. Hence the DWR algorithm achieves a better performance than LLR and WLCR. Most routing algorithms propose that increasing the number of pre-computed *k* routes can increase the routing options, thus reducing the blocking probability.

This, however, incurs a computational penalty. Our results also show that DWR does not increase the blocking probability when DTWR selects longer routes. Figures 5(b), 5(c) and 5(d) present the blocking results for NSFNet, EON and 5X5 meshtorus topologies. These results are obtained with 60,000 consecutive lightpath requests. Note that in dense networks, the blocking performance of the DWR algorithm is better than LLR and WLCR algorithms (e.g., EON or 5X5 meshtorus topologies).

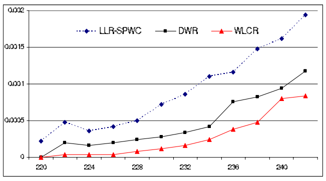
B. Performance comparison with WCs



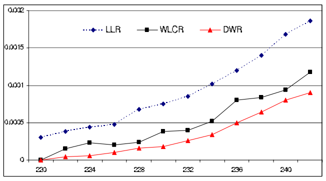
(a) The 6-node, 9-link topology (WCs at 3,4)



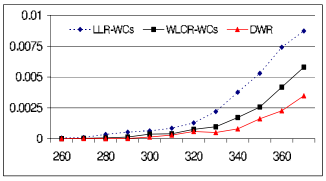
(b) NSFNet (WCs at 4,10)



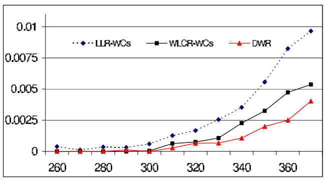
(c) NSFNet (WCs at 4,9,10)



(d) NSFNet (WCs at 4,9,11)



(e) EON (WCs at 1,9)



(f) EON (WCs at 1,4,9)

Fig. 6. Blocking performance (100%) to traffic load (Erlangs) with WCs in some topologies

The second scenario considers WC placement and uses the LLR and WLCR algorithms and compares their performance to the DWR algorithm. WCs are placed at nodes (3,4) in the 6-node, 9-link topology. Figure 6(a) shows the performance results of the modified network. The blocking performance of DWR in this case is better than WLCR. Also, both of these perform much better than LLR. We also vary the number and placement of WCs in the NSFNet and EON topologies, and achieve similar results. With WCs placed at nodes (4,10), (4,9,10), and (4,9,11) in the NSFNet topology, the results of Figures 6(b), 6(c) and 6(d), respectively, are obtained. In addition, WCs are placed at nodes (1,9) and (1,4,9) in the EON topology, and the results are shown in Figures 6(e) and 6(f). These results show that our proposed adaptive routing approach, without using WCs, has better performance than LLR and WLCR, even when sparse wavelength converters are placed in the network.

IV. Conclusion

In this paper, we have presented an adaptive routing approach, DWR, to address the routing and wavelength assignment problem in WDM networks without utilizing wavelength converters. Our simulation results show that the proposed DWR algorithm is able to efficiently reduce the network blocking probability and increase the wavelength utilization. We have also shown that the performance of DWR is better than LLR and WLCR, which are considered with or without sparse wavelength converters. Thus, cost-efficiency can be significantly improved by utilizing the proposed routing approach without placing any wavelength converter in the networks.

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