Dynamic Deflection Routing with Virtual Wavelength Assignment in Optical Burst-Switched Networks

***Abstract*— In optical burst-switched networks, one of the most significant issues is contention resolution. There have been several deflection routing techniques as contention resolution. While contention is resolved by traditional deflection routing, it can not guarantee that the control packet will reserve all wavelengths successfully to the destination on the alternate path, especially when traffic load is high in a network. Therefore, in this paper, we propose a Deflection Routing with Virtual Wavelength Assignment (DR-VWA) algorithm in order to provide more guarantee of resource for loss-sensitive traffic bursts. The proposed DR-VWA scheme 1) dynamically decides the alternate path with the least traffic load and 2) allows high-priority bursts in terms of loss to be assigned wavelengths virtually over the path. The proposed scheme is evaluated through simulation, and it is shown that significant improvement with regard to burst loss and wavelength conversion cost can be achieved.**

***Index Terms*— Optical burst switching, Deflection routing, Virtual Wavelength Assignment, Burst loss**

I. Introduction

Optical Burst Switching (OBS) has been proposed as a suitable switching paradigm to exploit the terabit bandwidth in Optical Internet. It tries to combine the best of both circuit and packet switching while avoiding their shortcomings. In Optical Burst-Switched (OBS) networks, control packet is sent first on a separate control channel ahead of a variable-length data burst (ranging from 10 kilobytes to 300 megabytes, for example) in order to reserve bandwidth resources prior to the arrival of each data burst on a data channel. That is, instantaneous circuit is established and the resources are occupied just until the burst is passed.

In an OBS (Optical Burst-Switched) network, contention resolution is necessary in order to handle the case where more than one burst are destined to go out of the same output port at the same time. Being realized that this is a severe problem which frequently arises in an OBS network, several contention resolution techniques have been proposed such as optical buffering, wavelength conversion, and deflection routing. Due to the immaturity in both optical buffering and wavelength conversion techniques, deflection routing has received a lot of attention most recently [1]-[5].

The deflection routing function implemented in each switch automates the alternate path setups when a control packet encounters a congested node over the primary path. Generally, deflection routing re-routes data on different links, resulting in much less resource contentions. Thus, reminding the fact that optical networks have very limited buffering and wavelength conversion capabilities, deflection routing has a salient advantage over other contention resolution schemes. However, it is worth mentioning that it can not be guaranteed that the control packet will reserve all the wavelengths successfully to the destination on the alternate path, especially when traffic load is high in a network [2]. Thus, in this paper, to reduce burst loss on the alternate path, we propose a dynamic Deflection Routing with Virtual Wavelength Assignment (DR-VWA) scheme. Unlike traditional deflection routing, the proposed DR-VWA allows some contending bursts from high priority traffic flows in light of loss to be transmitted on an alternate path with wavelengths assigned virtually. This implies that control packet should carry the information about the available wavelengths which were determined in advance over the path like in RWA (Routing with Wavelength Assignment). On the other hand, other contending bursts belonging to delay-sensitive traffic flows are routed via traditional deflection routing unless wavelength conversion is available.

Additionally, our proposed scheme attempts to seek the least congested alternate path before assigning wavelengths virtually while, usually, shortest path or least number of hops algorithm is used to define the optimum output at every router in an OBS network. Ultimately, the main objective of our paper is to reduce burst blocking rate by providing a higher probability of obtaining wavelength resource for high-priority contending bursts. In addition to burst blocking rate, the proposed scheme accounts for wavelength conversion cost while virtually assigning wavelengths. Even if in [5], the prioritized wavelength assignment system is proposed, that is compatible with deflection routing, the wavelength conversion is not considered in [5]. While the authors of [3] and [4] consider combination of wavelength conversion and deflection routing, their work is to simulate the combination without describing a specific algorithm. Thus, the proposed DR-VWA scheme seeks to capture the cost of converting wavelengths as well as burst loss, leading to reduction in both wavelength conversion cost and burst blocking rate.

Furthermore, heuristic algorithm is proposed for the DR-VWA scheme to reduce the computation complexity. It limits the distance of deflected path gaining from the benefit of reducing end-to-end delay which increases as traditional deflection routing tends to dramatically increase the length of deflected paths.

Through simulation experiments, we will show the performance of the proposed algorithm with respect to wavelength conversion cost and burst blocking.

II. Deflection Router Architecture

In this paper, ”hub node” concept proposed in [3] and [4] is adopted since some nodes in a network have enough higher out

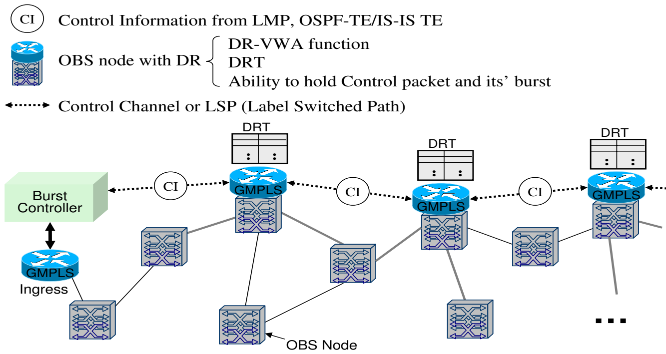

Fig. 1. Deflection routers with DR-VWA module and GMPLS plane in an OBS network

degrees than other nodes to serve as major deflection routing nodes. It is also beneficial in terms of development cost to use the "hub-node" concept now that all the nodes do not need to be equipped with the proposed DR-VWA module and FDL (Fiber Delay Line). In our work, we call the hub node deflection router.

It has been assumed that OBS nodes use predefined lookup Deflection Routing Tables (DRTs) to deflect contending bursts rather than drop them. In the same manner, deflection router maintains its DRT. When contention occurs, the DR-VWA module in the deflection router determines an alternate path on the basis of deflection routing policy (e.g. both traffic load status and distance to the destination in this paper), and then assigns suitable wavelengths virtually over the path. If there are wavelength converters at some nodes in a network, conversion cost is considered. Otherwise, the deflection router just seeks an available wavelength. Hence, the deflection router requires information about wavelength utilization. Such information can be kept in a centralized or distributed manner. In a centralized approach, only one server node keeps track of this information. However, under the condition of rapidly changing availability of resources, this centralized approach is not feasible. In a distributed approach, wavelength usage information could be obtained through periodic exchange of local wavelength utilization among the neighboring deflection routers. This kind of periodic information exchange may provide untimely information in OBS networks where wavelength assignment/release happens frequently. But even though deflection router fills control packet with accurate information about available wavelengths over the alternate path, it is possible for another burst to reserve one of the wavelengths carried in the control packet. Accordingly, we can assume the latter approach in this paper. Under this assumption, high priority contending bursts can have a higher probability of obtaining wavelength resource resulting in the reduction of burst blocking rate, as mentioned in Introduction.

To exchange information about link status, GMPLS can be employed as control signaling. Extended Interior Gateway Protocols (IGP) such as OSPF-TE/IS-IS TE and Link Management Protocol (LMP) of GMPLS are able to distribute network status information to DR-VWA module in deflection router. In addition to getting link status information, noting that the proposed DR-VWA scheme performs a kind of Explicit Routing (ER), it is desirable to exploit ER (i.e. traffic engineering) in GMPLS rather than developing new signaling protocol. ER is one of the primary reasons that GMPLS have been considered as a suitable common control plane over various multiple layer 2 architectures. For OBS, Labeled Optical Burst Switching (LOBS) was already proposed to augment OBS nodes with IP/MPLS controllers [6] and the authors of [7] also proposed GMPLS-based photonic burst switching architecture.

III. Deflection Routing With Virtual Wavelength Assignment

A. Network Cost Model and Problem Formulation

We now provide a formulation of the deflection routing problem with virtual wavelength assignment. In the deflection routing problem formulation, the network topology,a set of attributes pertaining to the resources and the constraints in the network are defined. The burst demands that are to be routed through deflected path in the network are described by a set of attributes as well. Then, the problem is to find an optimal alternate path minimizing a network cost function. Let us first introduce the relevant network elements. Consider a physical network represented by a graph $G(N, L)$ where N is the set of nodes and L the set of links (*i.e.* fibers) connecting the nodes. It is assumed that W is the maximum number of wavelengths per fiber. Given the set of established primary lightpaths, $\mathbf{P}$ for the ongoing bursts, $P_p \in \mathbf{P}$, now make assumption that an alternate path, P is established, for the contending burst.

Differently from traditional deflection routing techniques we chose to minimize a cost function which explicitly accounts for the cost at both the optical and at the electronic level. The choice of the objective function to be minimized is driven by the following considerations:

- By minimizing the cost of blocking over the path, we try to minimize the global average blocking primarily caused by contention in OBS networks. Even under low traffic load, if most of the traffic bursts are mistakenly engineered over the same route, frequent contentions becomes inevitable.
- The DR-VWA algorithm assigns wavelengths virtually to the alternate path minimizing the cost for wavelength conversion.
- We minimize the wavelength conversion cost at the switches, the blocking cost and the cost for traversing the links on some wavelength over alternate path, jointly.

Thus, in our formulation we introduce three network costs C_c, C_t,and C_b denoting wavelength conversion cost, transmission cost and the cost of contention for P. For each link and each node, C_i^{kl}, C_{ij}^t, C_{ij}^b denote the cost of wavelength conversion from wavelength k to l at node i, the transmission cost on link (i, j), and the cost of blocking due to contention from node i to node j ($i \neq j$), respectively.

The above defined wavelength conversion costs accommodate the general case where conversion costs depend on the nodes and wavelengths involved. That is, for example, in a simple manner, the costs can be easily decided in such a way that the least numbered available wavelengths are used first, while the costs can be dynamically adjusted to changing network conditions.

In this problem formulation, the objective function is designed to establish an alternate path, P for the contending burst from the congested node to the destination such that the above three network costs are minimized.

The relevant indicators are:

- $x^k_{ij,p}$ is a binary variable telling whether wavelength k is already reserved on link (i,j) over P_p.
- x^k_{ij} is a binary variable telling whether the contending burst uses wavelength k on link (i,j) over P.
- $y^{kl}_{i,p}$, y^{kl}_i are binary variables telling whether wavelength k needs to be converted to l at node i on P_p and P, respectively.
- x_{ij} is a binary variable denoting whether alternate route includes a link (i,j) (*i.e.* $\sum_{k=1}^{W} x^k_{ij} > 0$) or not

The objective function is stated as

$$\text{Minmize} \qquad \sum_{i=1}^{|N|}(C_c + C_t + C_b) \tag{1}$$

where

$$\begin{aligned} C_c &= \sum_{l=1}^{W}\sum_{k=1}^{W} C^{kl}_i y^{kl}_{i,d} \\ C_t &= \sum_{j=1}^{|N|}\sum_{k=1}^{W} C^t_{ij} x^k_{ij,d} \qquad i \neq j \\ C_b &= \sum_{j=1}^{|N|} C^b_{ij} x_{ij} \end{aligned} \tag{2}$$

The set of constraint conditions is are defined as follows:

$$\sum_{l=1}^{W}\sum_{k=1}^{W} y^{kl}_i = \sum_{k=1}^{W}\sum_{j=1}^{|N|} x^k_{ij} \tag{3}$$

$$\sum_{k=1}^{W}(y^{kl}_i + y^{kl}_{i,p}) \leq 1, \;\; \sum_{l=1}^{W}(y^{kl}_i + y^{kl}_{i,p}) \leq 1, \;\; \forall P_p \in \mathbf{P} \tag{4}$$

$$\sum_{j=1}^{|N|}\sum_{k=1}^{W}(x^k_{ij,p} + x^k_{ij}) \leq W, \; \forall P_p \in \mathbf{P} \tag{5}$$

At a node, Eq. 3 ensures wavelength conversion, while Eq. 4 requires that a specific wavelength only appears at most once in both the incoming and outgoing links. Eq. 5 ensures, in a link, that the number of wavelengths occupied by both primary and deflected paths should not be larger than that provided by a link.

In this problem formulation, it is assumed that a burst offered to a path uses a single wavelength channel and maximum burst length is no larger than the link transmission capacity. Accordingly, each burst occupies only one wavelength on the link.

Given weighting factors, the objective function Eq. 1 can be restated as

$$\text{Minimize} \qquad \sum_{i=1}^{|N|}(\alpha C_c + \beta C_t + \gamma C_b) \tag{6}$$

where the weighting factor is usually supplied by the network manager or carriers responsible for designing the network cost.

Regarding C^b_{ij}, data on current blocking status is collected periodically [8] by control signaling such as GMPLS as explained in Section II as burst blocking or dropping rate. Now, note that Internet traffic is very bursty. The burstiness of Internet traffic results in on periods of packet arrivals forming burst trains followed by idle periods. Thus, the measured sample blocking rate is not directly applied to C^b_{ij} but the average is used, which takes into account the history of measurements. That is, to estimate the measured blocking rate, the well-known Exponential Weighted Moving Average (EWMA) can be applied. Upon obtaining a new measured blocking rate, $C^{b(k)}_{ij}$ at time instant t_k, a new estimation $\bar{C}^b_{ij}$ is calculated as $\bar{C}^{b(k)}_{ij} = (1-w)\bar{C}^{b(k-1)}_{ij} + C^{b(k)}_{ij}$ where w is the exponential weight. As we know, the difficulty lies in the proper choice of w. Besides, there is no known OBS Internet traffic measurements. Therefore, thorough analysis of the traffic over an OBS testbed must be a future research topic even though there is an ongoing experiment [9]. It is out of the scope in this paper.

B. Heuristic DR-VWA

In the DR-VWA algorithm described in the previous Section III-A, an alternate path is computed online for the contending burst when contention occurs. Thus, the alternate path from the congested node to the destination node is chosen on-demand depending on the current network state. We could know that the it has a computation complexity of $O(|N|^2W + |N|W^2)$ to see the problem formulation in the previous Section III-A. To decrease the complexity and support the real-time on-demand DR-VWA, the heuristic DR-VWA algorithm is proposed.

Because it is not cost-effective under current technology to implement the modules related to the DR-VWA and wavelength converter such as electronic regenerator at all the OBS nodes in a network, these costly modules are incorporated into deflection routers which have higher out degrees. Alternate paths to each destination reachable from a deflection router are maintained in Deflection Routing Table (DRT) on the deflection router. The paths in the DRT are computed offline periodically as well as online. For the set of all the paths in the DRT, we use notation $\mathbf{P}_{\text{DRT}}$ which contains the alternate paths for each destination.

In the heuristic DR-VWA, there is a relaxation procedure that limits the distance over alternate path. This relaxation is not posed only to reduce the end-to-end delay resulting from lengthening alternate path but also to reduce the size of DRT at deflection router. This reduction of DRT size also speeds up the computation.

Meanwhile, there is a problem that the contending burst can suffer from insufficient offset time, thus it has to be dropped even with deflection routing. That is, when the contending burst is redirected to the alternate path, the offset time on the alternate path is different from (usually, longer than) that on the primary path. One solution to this problem is to render sufficient extra offset time to each burst while the other is

TABLE I
THE PROCEDURE OF THE HEURISTIC DR-VWA ALGORITHM

INPUT: $G(N, L)$, $\bar{\mathbf{P}}$, $\mathbf{P}_{\text{DRT}}$, C_i^{kl}, C_{ij}^t, C_{ij}^b, t_o, t_b
OUPUT: P

Procedure Heuristic DR-VWA()
\\ Initialization of DRT
$\mathbf{P}_{\text{DRT}}$ = FindAlternatePathLimitingDistance(N, L, t_o, t_b, n);
ComputeCost($\mathbf{P}_{\text{DRT}}$, C_{ij}^b);
\\ in ascending order
SortAlternatePath($\mathbf{P}_{\text{DRT}}$);
\\ On-demand when there is contention
While (contention)
\\ e.g. burst length, traffic class
$Burst$=GetBurstAttribute(ControlPacket);
P=SelectLeastCongestedAlternatePath($\mathbf{P}_{\text{DRT}}$);
If ($Burst$ is loss-sensitive)
Then P=AssignVirtualWavelenghs(P, $Burst$, C_i^{kl}, C_{ij}^t);
If (No Available Wavelengths)
Then Drop the burst;
Notify the source that the burst is dropped;
Go back to while loop;
EndIf
EndIf
EndWhile

making the control packet reserve Fiber Delay Line (FDL) to delay the burst. For the latter, each deflection router should be equipped with FDL buffer. Even though the above problem is resolved, it may happen that the too much increased distance on the deflected path cause longer delay than expected offset time or buffering time.

Here, a contention is assumed to occur on a deflection router after the contending burst has passed H_c hops. The number of the traversed hops, H_c is obtained from the control packet. Let t_o denote the extra offset time of the contending burst, which consists of basic offset time and extra offset time. Additional constraint for offset time is defined as

$$\sum_{k=1}^{W}(x_{ij}^k \sum_{(i,j)\in P} H_d) \leq t_o - H_c\delta \tag{7}$$

where H_d denotes the number of hops over the alternate path and $t_o > H_c\delta$. In case that FDL is available on the deflection router, the Eq. 7 is expressed as

$$\sum_{k=1}^{W}(x_{ij}^k \sum_{(i,j)\in P} H_d) \leq t_o + t_b - H_c\delta \tag{8}$$

where t_b depends on the length of FDL as buffered delay limit.

The proposed heuristic DR-VWA algorithm limits the distance of alternate path in order to keep the contending burst from overtaking the control packet due to the lack of offset time. Note that it is not only possible but also more realistic to limit the distance of alternate path to avoid longer end-to-end delay than tolerable delay limit. The procedure of the heuristic DR-VWA algorithm is shown in Table I.

The heuristic DR-VWA procedure is run on deflection routers as mentioned in Section I. When more than one control packet try to reserve the same out port, in our scheme, the longest burst (or delay-sensitive burst) reserves the out port to decrease the data loss rate (or the end-to-end delay). The FindAlternatePathLimitingDistance in the above algorithm, searches all possible alternate paths to each destination limiting the distance and initializes the DRT with the found alternate paths. It plays the role of keeping offset time like in Eq. 7 or 8 by putting a limitation on the distance of alternate path. The module ComputeCost computes the blocking cost of the alternate paths in DRT and then the paths are sorted in ascending order by the SortAlternatePath module. When a contention occurs, the deflection router is ready for delaying the contending data burst reading the length of the burst in the control packet. As soon as the procedure determines P, the deflection router sends the data burst. Accordingly, it is more beneficial that the deflection router has a buffer which is either optical or electronic.

IV. SIMULATION

In order to verify the benefits of our proposed technique, we compare the heuristic DR-RWA algorithm to Shortest Path Deflection Routing (SPDR) and Wavelength Conversion (WC) schemes. For each scheme, we used the same scenarios and parameter values listed in Table II. Our simulation model accounts for the number of the wavelength cost as well as for the burst drop rate, as performance metrics. All the simulations results are obtained on a 14-node NSFNET network with 26 links shown in Fig. 2, where the numbers on the links represent link distances in units of km. Each link (or fiber) is composed of the same number of wavelengths, W. Nodes WA, CA2, MI and MD are configured with full wavelength conversion capabilities for both the DR-VWA and WC except that wavelength conversion functions at deflection router when contention occurs for the WC. UT, PA and TX are deflection routers with the DR-VWA algorithm. Five pairs of source and destination node are randomly chosen for each simulation test.

TABLE II
SIMULATION PARAMETER VALUES

Parameter	Values
Wavelengths	4, 8, 16, 32
Average burst length	1Mbyte
Channel bandwidth	10 Gbps
Traffic load	0.5-0.9

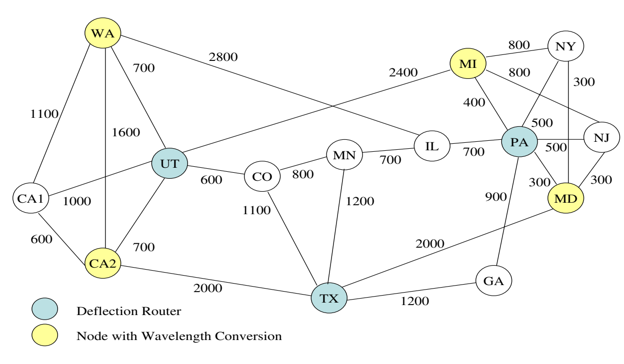

Fig. 2. 14 node NSFNET network with 24 links

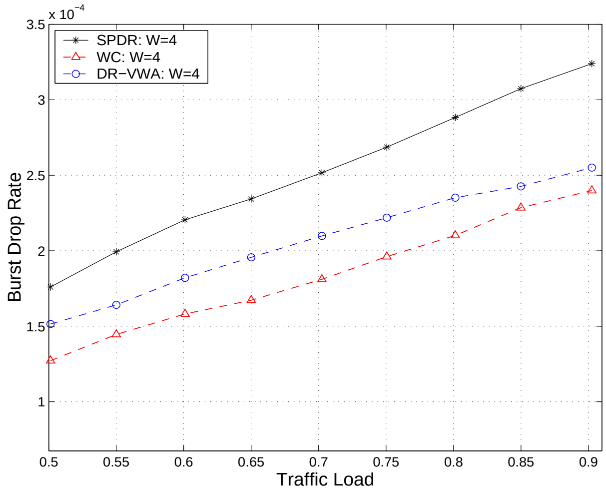

Fig. 3. Burst drop rate (W=4)

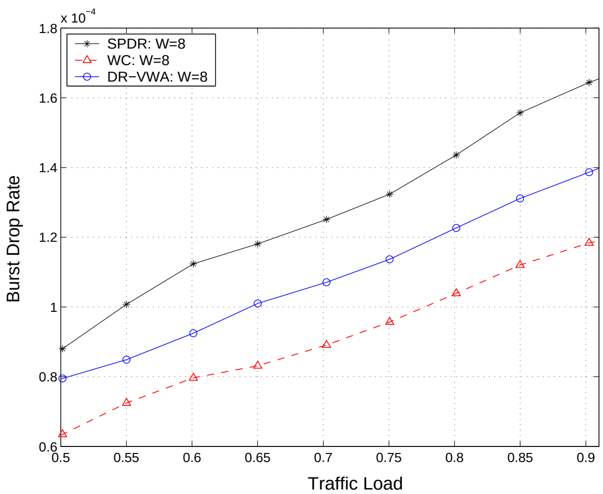

Fig. 4. Burst drop rate (W=8)

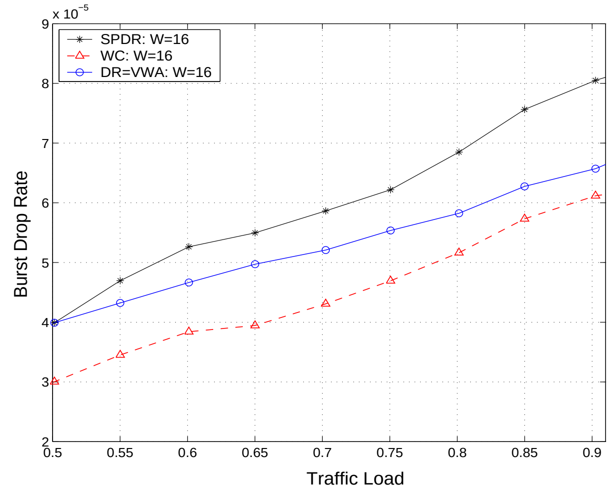

Fig. 5. Burst drop rate (W=16)

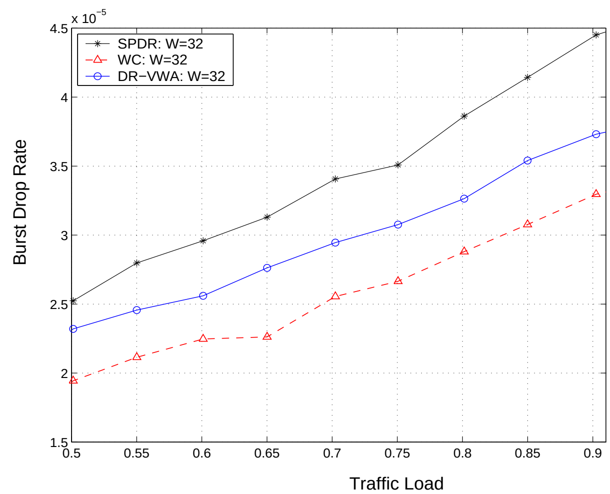

Fig. 6. Burst drop rate (W=32)

It is assumed that burst arrivals follow the Poisson process and their lengths are exponentially distributed with mean 1Mbyte. In our simulation model, while, for the SPDR algorithm, buffer such as FDL is placed at every node, only deflection routers have a buffer for the proposed algorithm, to delay the contending burst. As a resource reservation mechanism, delayed reservation with void filling is applied to our simulation tests.

Figures 3, 4, 5 and 6 plot the burst drop rate versus load for DR-VWA, SPDR and WC. Note that the for all W=4 and 8, the burst drop rate of the DR-VWA is much lower than the SPDR at most loads. As the results indicate, the shorter deflected path cannot guarantee a lower burst loss. For example, although the DR-VWA algorithm possesses a higher average hop-number than that the SPDR algorithm, it can obtain a lower burst drop rate. This is because the DR-VWA transmits the contending burst over the alternate path with minimum blocking rate and provides the information of available wavelengths as well as out port to the contending burst.

As we expected, the DR-VWA has higher loss as compared to the WC scheme where instead of being transmitted on an alternate path, one optical signal is converted into a different available wavelength given a wavelength converter at each deflection router. The Figures 3, 4, 5 and 6 indicate that the WC gets better performance in terms of burst drop rate trading off the expensive wavelength conversion cost. Although the benefit of wavelength conversion is obvious from these results about the burst drop performance, under current technology, adding wavelength conversion capabilities to optical switches will definitely increase its complexity and cost.

Table III shows the relative performance improvement of the wavelength conversion cost by the proposed DR-VWA in comparison to the WC under varying traffic loads. In our simulation environment to get these results regarding wavelength conversion cost, we assumed the cost of wavelength conversion between any two different wavelengths is 1 [10]. Note that there is over 60% reduction in wavelength conversion cost. We can see that this improvement comes from using deflection routing. From this Table, we again observe that WC enhances burst drop performance at the expense of wavelength conversion cost, while the DR-VWA keeps wavelength conversion cost low maintaining moderate burst

TABLE III
WAVELENGTH CONVERSION COST IMPROVED BY DR-VWA IN COMPARISON TO WC

Load	W=4	W=8	W=16	W=32
0.5	66.7%	69.5%	71.4%	60.8%
0.55	66.1%	68.3%	70.6%	63.5%
0.6	66.1%	67.9%	69.8%	63.8%
0.65	66.7%	68.8%	70.5%	66.2%
0.7	66.4%	68.3%	69.4%	63.9%
0.75	66.1%	68.2%	68.5%	64.6%
0.8	66.3%	68.1%	67.5%	64.8%
0.85	66.2%	67.3%	65.8%	64.5%
0.9	66.5%	67.4%	65.8%	64.2%
0.95	66.5%	67.8%	66.7%	64.6%

drop rate which is much better than what the SPDR achieves.

V. CONCLUSION

In this paper we studied the problem of designing deflection routing for optical burst-switched network assigning available wavelengths virtually. Even though, in fact, it is hard to obtain an exact knowledge about network resource in an OBS network under dynamic traffic, wherein bursts arrive to and depart from the network in a random manner, the proposed DR-VWA scheme aimed to reduce the burst dropping rate by finding alternate routes in an optimized fashion of avoiding contention and assigning proper wavelengths virtually. Moreover, the DR-VWA also took the wavelength conversion cost into account as one of main performance metrics to assign wavelengths virtually over an alternate path.

Via simulation tests, we have shown that the DR-VWA achieves better burst drop performance than SPDR while it can keep wavelength conversion cost lower maintaining moderate burst drop rate compared with wavelength conversion mechanism without deflection routing.

Our future research is extending the proposed virtual wavelength assignment algorithm to the OBS edge nodes, in a manner of hybrid switching that will allow maximum loss guarantee for high priority traffic utilizing network resources efficiently.

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