Explicit Routing for Traffic Engineering in Labeled Optical Burst-Switched WDM Networks*

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Abstract. Optical burst switching (OBS) is a promising technique for supporting high-capacity bursty data traffic over optical wavelength-division-multiplexed (WDM) networks. A label-switched path can be established to forward a burst control packet (BCP) if each OBS node is augmented with an IP/MPLS controller. Such a network is called a labeled OBS (LOBS) network, and it can exploit the explicit routing and constraint-based routing properties supported in the MPLS framework to perform traffic and resource engineering. In this paper, we consider the traffic-engineering problem in a LOBS network, using explicit routing to balance network load and to reduce the burst-loss probability. We model the traffic-engineering problem in a LOBS network as an optimization problem and propose two new objective functions to minimize network congestion. Our illustrative numerical examples show that the burst-loss probability can be significantly reduced using optimization technique, when compared with shortest-path routing.

1 Introduction

Optical burst switching (OBS) technology has been proposed and studied as a promising technique to support high-speed data traffic over optical wavelength-division-multiplexed (WDM) networks [1]-[3]. The basic idea of OBS is to assemble data packets into large-size bursts at the ingress node, and then to send a burst into the network shortly after a corresponding control message is sent out, without waiting for any acknowledgement message. The control message, usually called burst control packet (BCP), typically uses a separate control channel and is processed electronically at each node through which it traverses. Thus, the

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node can configure its switch for the incoming burst according to the information carried by the BCP (such as when the burst will arrive and how long it will hold). The data burst does not need to be converted into electronic domain for processing. It can optically cut through the switching nodes and reach the destination. Through this approach, the electronic bottleneck of the optical-electric-optical (OEO) conversion occurring at the switching nodes can be eliminated.

However, data bursts from different traffic flows can share the same bandwidth on a link using statistical multiplexing. And a data burst will be dropped if contention occurs at a switching node in an OBS network with no or limited fiber delay lines (FDLs). Actually, the probability of contention for two bursts at an output link will increase if the load on the link is heavy. Thus, if the traffic can be evenly distributed or balanced over all links when it is routed, the burst blocking (or loss) probability can be greatly reduced. Hence, we investigate the traffic-engineering problem (i.e., *"put the traffic where the bandwidth is"*) in OBS networks and design intelligent routing algorithms to achieve such an objective.

In today's Internet, IP routing generally employs destination-based shortest-path routing, in which a packet is routed or forwarded according to its destination prefix at a router. Even though this routing approach can scale gracefully when network size increases, destination-based routing usually creates congested links and unbalanced traffic distribution [4]. This problem can be solved if the traffic is properly engineered using explicit-routed paths. In a MultiProtocol Label Switching (MPLS) controlled network, explicit routes are supported by establishing label-switched path (LSPs). If an OBS node is augmented with an IP/MPLS controller, the node will become a labeled OBS (LOBS) node, and it functions as a label-switched router (LSR). In such a LOBS network, a BCP will be attached a label before it is sent out on the network, and the label is swapped when the BCP is processed at each intermediate node. Both explicit routing and constraint-based routing supported in the MPLS framework can be extended to provision and engineer traffic to better utilize network resource in a LOBS network [1].

An explicit route simply performs as a point-to-point logical connection in a LOBS network. The collection of such logical connections between the various pairs of nodes essentially form a virtual network on top of the physical fiber network topology. Each explicit route is a "virtual link" of the "virtual topology". All BCPs sent out on an explicit route will follow the path through to the destination. Theoretically, any arbitrary virtual topology can be pre-planned and set up based on the traffic intensity (including full-mesh topology and topologies with more than one virtual links between a node pair). One of the main issues that needs to be addressed in a LOBS network is how to compute the explicit routes so that traffic is balanced in the virtual topology and the burst-loss probability is minimized by reducing the probability of burst contention at the various nodes.

An explicit route can be calculated either dynamically (based on "current" network resource availability) or statically. Dynamic routing can achieve better load balancing if the network resource information is accurate. However, to support dynamic routing, the network may need to be flooded by frequent network-resource-update messages, and additional signaling protocols or extensions of current signaling protocols may need to be developed. Pre-planned (static) routing can avoid such signaling overhead. And most importantly, optimization techniques can be applied in pre-planned routing such that a virtual topology is established based on a given traffic intensity matrix. Given that the physical topology of an optical network is relatively stable (i.e., this topology changes less frequently than that in an IP network), periodic or threshold-triggered rerouting of the virtual topology using optimization techniques can be performed easily to adapt to changing traffic intensities.

In this paper, we investigate the problem of pre-planned explicit routing for traffic engineering in a LOBS network. As mentioned in [1], for traffic engineering in a LOBS network, we need to address various issues unique to LOBS such as potentially excessive burst dropping due to the absence of or limited use of FDLs at the LOBS nodes when contention occurs. To tackle this situation, we model the problem of explicit routing for traffic engineering as an optimization problem with the objective of minimizing the link congestion.

The remainder of the paper is organized as follows. Section II reviews previous work, discusses the shortcomings of the objective function presented in previous work, and proposes two new objective functions to minimize congestion. In Section III, we apply pre-planned explicit routing to LOBS networks and study the performance of different objective functions using illustrative numerical examples. Section IV concludes this study and discusses future research directions.

2 Optimal Routing for Load Balancing in a LOBS Network

The problem of how to set up explicit routes between pairs of nodes so that network congestion can be minimized has been studied in [5]. Even though the authors in [5] considered explicit-routing algorithms for Internet traffic engineering instead of LOBS networks, their objective is essentially the same as our objective: namely, set up explicit routes and minimize network congestion. Therefore, we first briefly review the optimization approach proposed in [5], discuss our approaches, and then compare the two methods.

The authors in [5] formulated the problem as a linear program. To minimize network congestion or balance traffic distribution, the optimization objective they proposed is to minimize the maximum of all link utilizations. The Integer Linear Programming (ILP) formulation used in [5] (denoted as ILP-A here) is summarized below.
ILP-A:

- *Notations:*
  - i and j denote end points of a physical fiber link.
  - s and d denote source and destination of a given traffic flow.
- *Given:*
  - $G = (V, E)$: network topology with node set V and edge set E.
  - C_{ij}: capacity of link (i, j).
  - D_{sd}: bandwidth requirement of traffic flow from node s to node d.

- *Variables:*
  - X_{ij}^{sd}: $X_{ij}^{sd} = 1$ if traffic flow (s, d) is routed through fiber link (i, j); otherwise, $X_{ij}^{sd} = 0$.
  - α: maximal link utilization across the entire network. $\alpha \geq 0$.
- *Objective A:* Minimize the maximum link utilization.

$$Minimize : \alpha + r \sum_{s,d \in V} \sum_{(i,j) \in E} X_{ij}^{sd} \quad (1)$$

  where r is a positive number which is assigned a small value such that minimizing α will maintain higher priority.
- *Constraints:*
  - On physical route flow-conservation constraints:

$$\sum_{(k,j) \in E} X_{kj}^{sd} - \sum_{(i,k) \in E} X_{ik}^{sd} = 0 \ \ if \ \ k \neq s, d \ \ \forall k \in V, \forall s, d \in V \quad (2)$$

$$\sum_{(s,j) \in E} X_{sj}^{sd} - \sum_{(i,s) \in E} X_{is}^{sd} = 1 \ \ \forall s, d \in V \quad (3)$$

  - On link-capacity constraints:

$$\sum_{s,d \in V} D_{sd} X_{ij}^{sd} \leq C_{ij} \alpha \ \ \forall (i, j) \in E \quad (4)$$

Note that the second term $r \sum_{s,d \in V} \sum_{(i,j) \in E} X_{ij}^{sd}$ in the objective function (i.e., Objective A) tries to avoid loops and unnecessarily long paths in routing.

Through Objective A, the authors in [5] expect that the traffic is moved away from the congested links, and traffic load is balanced across the network. However, we can see that minimizing network congestion or balancing load can not be strictly quantified. It is straightforward to see that minimizing the maximum link utilization can help reduce congestion but it cannot guarantee that the burst-loss probability is the minimum for all possible routings. For example, given two routings (routing 1 and 2) with the same α, load distribution on all the links is another parameter to evaluate how well the load is balanced. If more number of links in routing 1 have load close to α than that in routing 2, we can expect that a network with routing 1 will have larger burst-loss probability than that in a network with routing 2.

Therefore, improvements need to be made to further balance the load given the optimized maximum link utilization (i.e., α) in the network. Based on this observation, we propose two new objectives:

- Objective B: Minimize the number of links whose utilization is larger than a Watermark.
- Objective C: Minimize the sum of consumed bandwidth (or load) on links whose utilization is larger than a Watermark.

The Watermark is a positive integer, and it is smaller than α. In Objectives B and C, α provides a "ceiling" on the link load, which means that no link can have a load larger than α. Watermark provides a threshold, and a link will be marked as "(relatively) highly loaded" if its load is larger than the Watermark. With Objective B, we can ensure that the load on a link can exceed the threshold only when necessary. With Objective C, we can ensure that load on a link can only exceed the threshold by the minimum amount. With these two objectives, traffic will be shifted from heavily-loaded links to lightly-loaded links even when α is fixed.

We develop the ILP formulations for Objective B and C as follows (denoted as ILP-B and ILP-C, respectively).
ILP-B:

– *Objective B:* Minimize the number of links whose utilization is larger than Watermark.

$$Minimize : \sum_{(i,j)\in E} Y_{ij} + r \sum_{s,d\in V} \sum_{(i,j)\in E} X_{ij}^{sd} \tag{5}$$

– *Constraints:*
  - On physical route flow-conservation constraints:

$$\sum_{(k,j)\in E} X_{kj}^{sd} \; - \; \sum_{(i,k)\in E} X_{ik}^{sd} \; = \; 0 \;\; if \;\; k \neq s,d \;\; \forall k \in V, \forall s,d \in V \tag{6}$$

$$\sum_{(s,j)\in E} X_{sj}^{sd} \; - \; \sum_{(i,s)\in E} X_{is}^{sd} \; = \; 1 \;\; \forall s,d \in V \tag{7}$$

  - On link-capacity constraints:

$$\sum_{s,d\in V} D_{sd} X_{ij}^{sd} \; \leq \; C_{ij}\alpha \;\; \forall (i,j) \in E \tag{8}$$

  - On load-balancing constraints:

$$\sum_{s,d\in V} D_{sd} X_{ij}^{sd} \; - \; Watermark \; \leq \; pY_{ij} \;\; \forall (i,j) \in E \tag{9}$$

ILP-C:

– *Objective C:* Minimize the sum of consumed bandwidth (or load) on links whose utilization is larger than a Watermark.

$$Minimize : \sum_{(i,j)\in E} Z_{ij} + r \sum_{s,d\in V} \sum_{(i,j)\in E} X_{ij}^{sd} \tag{10}$$

– *Constraints:*
  - On physical route flow-conservation constraints:

$$\sum_{(k,j)\in E} X_{kj}^{sd} \; - \; \sum_{(i,k)\in E} X_{ik}^{sd} \; = \; 0 \;\; if \;\; k \neq s,d \;\; \forall k \in V, \forall s,d \in V \tag{11}$$

$$\sum_{(s,j)\in E} X_{sj}^{sd} \; - \; \sum_{(i,s)\in E} X_{is}^{sd} \; = \; 1 \;\; \forall s,d \in V \tag{12}$$

  - On link-capacity constraints:

$$\sum_{s,d\in V} D_{sd} X_{ij}^{sd} \; \leq \; C_{ij}\alpha \;\; \forall (i,j) \in E \tag{13}$$

  - On load-balancing constraints:

$$\sum_{s,d\in V} D_{sd} X_{ij}^{sd} \; - \; Watermark \; \leq \; Z_{ij} \;\; \forall (i,j) \in E \tag{14}$$

Note that, in both ILP-B and ILP-C, α is used as a constant and its value is optimized using ILP-A. In ILP-B, Y_{ij} is a new variable defined as follows: $Y_{ij} \in \{0,1\}$; $Y_{ij} = 1$ if load on link (i,j) is larger than Watermark; otherwise, $Y_{ij} = 0$. In Eqn. (9), p is a positive integer and is larger than $\alpha - Watermark$. p is introduced to ensure that $Y_{ij} = 1$ only when load on link (i,j) is larger than Watermark. In ILP-C, Z_{ij} is a new variable defined as follows: $Z_{ij} \geq 0$; $Z_{ij} = \sum_{s,d \in V} D_{sd} X_{ij}^{sd}$ if load on link (i,j) is larger than Watermark; otherwise, $Z_{ij} = 0$.

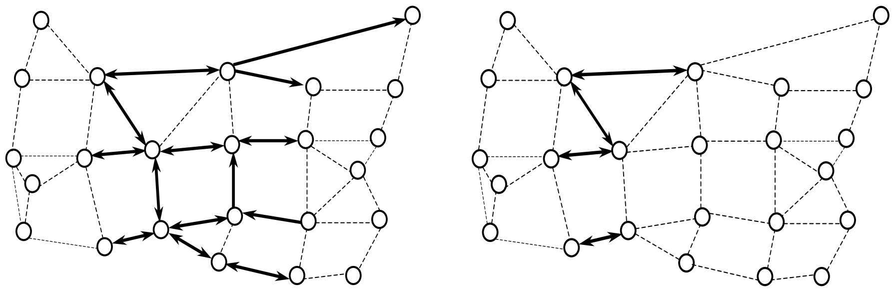
3 Illustrative Numerical Examples

We study the performance of pre-planned routing in LOBS networks without any FDLs. As we have discussed in Section 1, each node is equipped with an IP/MPLS controller, which could route a BCP according to the label attached to it. All bursts between the same node pair will follow an explicit route (i.e., a label-switched path). In LOBS networks, burst-loss probability is mainly determined by the load of the links the burst traverses. It is also affected by the number of hops in the explicit route. If a burst needs to travel more hops, the burst will encounter higher loss probability if we assume the same load, and thus same loss probability, on each link.

Figure 1 shows the network topology we used in this study, which is a representative US nationwide network with 24 nodes and 86 unidirectional links. Each edge in Fig. 1 is composed of two unidirectional fiber links, one in each direction. Each fiber link is assumed to have 8 data channels and 1 control channel. Each channel operates at 10 Gbps. We simulate Poisson traffic at each node and the destination of a burst is uniformly distributed among all other nodes. The length of each burst follows a negative exponential distribution with mean value 10^5 bits. Contention on the control channel is ignored as the size of a BCP is usually small. The offset time for a burst is assigned as $H * t_p$, where H is the hop distance of the explicit route the burst will take and t_p is the average processing time for a BCP at a node, which is assumed to be 1/10 of the mean burst length in this study. In addition, we assume that each node has full wavelength-conversion capability. The measured performance metrics include burst-loss probability and average hop distance.

We first pre-plan four different routings for uniform traffic: shortest-path routing, as well as optimized routing using ILP-A, ILP-B, and ILP-C. We assume one unit traffic flow for each source-destination node pair. Table 1 shows the characteristics of the four routing tables. Comparing shortest-path routing with ILP-A, we can see that 53 flows traverse the most congested link (i.e., $\alpha = 53$) in shortest-path routing but only 32 flows use the most congested link (i.e., $\alpha = 32$) in ILP-A, while the total hop distance (sum of the hop distance of all the flows) only increases by 6. This indicates that Objective A (minimize the maximum of link utilization) is effective in moving the traffic away from the congested links without affecting the hop distance too much.

In ILP-B, Watermark is fixed at 29, so the number of links with load larger than 29 (these link are denoted as heavily-loaded links) is minimized. We find



(a) After routing is optimized using ILP-A (b) After routing is optimized using ILP-B

Fig. 1. A sample network topology. The dark lines are links with more than 29 flows traversing on them (while arrows indicate in which direction)

Table 1. Characteristics of pre-planned routing tables

	Watermark	α	Total hop distance
Shortest-path routing	N/A	53	1652
ILP-A	N/A	32	1658
ILP-B	29	32	1672
ILP-C	20	32	1682

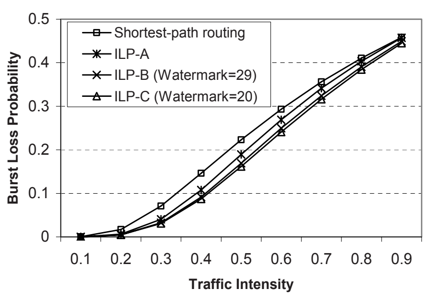


Fig. 2. Burst-loss probability

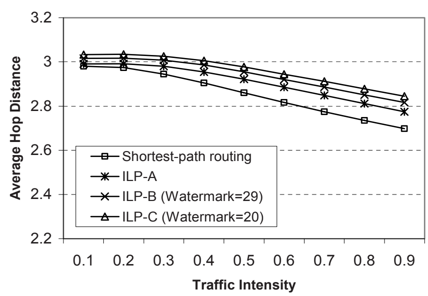


Fig. 3. Average hop distance

that only 8 links are heavily-loaded links and each of them have 32 flows in ILP-B, while in ILP-A, 24 links have load more than 29. In Fig. 1(a), we identify these 24 links in ILP-A with dark lines and in Fig. 1(b), we show the 8 heavily-loaded links in ILP-B with dark lines. We notice that these 8 links create two cuts (one from east to west and the other from west to east) in the network. One can see that, when one of the cuts is fulfilled, α cannot be reduced below the maximal link load on the cut. However, the load on other links in the network can be reduced, as shown in Fig. 1(b).

In ILP-C, Watermark is fixed as 20, which is the average number of flows (i.e., load) on a link. We choose the average link load as Watermark so the total load that exceeds the average load is minimized using ILP-C.

Figure 2 shows the burst-loss probability when we plug in the routing tables into the LOBS network. It shows that the burst-loss probability is reduced by 15%-80% (when load is less than 0.5) when routing is optimized using ILP-A compared with shortest-path routing. This is because congestion is removed in optimized routing, so the burst-loss probability is dramatically reduced. The burst-loss probability is further reduced by 15%-30% (when load is less than 0.5) using ILP-B and ILP-C, compared with ILP-A. This is because load on the "heavily-loaded" links can be further balanced using ILP-B and ILP-C, but ILP-A stops when α is optimized. ILP-C achieves the best performance because it directly minimizes the load on heavily-loaded links instead of minimizing the number of heavily-loaded links as in ILP-B; and, as we have mentioned before, the load determines the burst-loss probability. In Fig. 2, the performance gain reduces when the load increases. This is due to the fact that more short-hop bursts will succeed when the load is heavy.

Figure 3 shows the average hop distance for the pre-planned routings. As opposite to the burst-loss probability, shortest-path routing has the minimum average hop distance, which is because every burst takes the shortest path in shortest-path routing. For optimized routings, ILP-A performs best, ILP-C performs worst, and ILP-B is in between, which is comparable to the total hop distance shown in Table 1.

4 Conclusion

We considered the problem of explicit routing for traffic engineering in LOBS networks. We formulated the traffic-engineering problem as a linear program and proposed two novel objective functions to minimize congestion. The illustrative numerical results showed that the proposed optimization approaches can significantly reduce the burst-loss probability without too much sacrifice in the average hop distance for a burst. Traffic bifurcation will be studied using the optimization approach, which is our future research direction.

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