On the Benefit of Fast Switching in Optical Networks

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Abstract: Though the benefit of wavelength switching in WDM networks is well understood, that of fast switching at packet/burst level is not. We show that fast switching can further reduce wavelength resources and OEO conversion.

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1. Introduction

It is well understood that a switched WDM optical network using wavelength switches such as ROADMs is more resource efficient than its statically configured counterpart in terms of e.g., the number of wavelengths and OEO conversions needed in the network to satisfy the same set of traffic demands (which in practice are time-varying), or achieve the same connection request blocking performance given the same amount of resources.

Yet, the benefit (or resource efficiency) of using fast optical switching fabrics that can switch at the packet or burst level based on e.g., PLZT [1] is not well known, mainly due to the lack of apple-with-apple performance comparisons between a WDM network with wavelength switches and another one with fast switches based on common requirements and metrics. More specifically, in a WDM network with wavelength switches, optical circuits in the form of wavelength paths are provisioned to provide guaranteed bandwidth services to data flows (i.e., OCS is implemented). When there is a traffic surge, without additional wavelength resources available, all requests for additional circuits are blocked. In a WDM network with fast switches, data is sent in the form of packets or bursts using OPS/OBS. Such a network usually does not provide bandwidth guarantee to any data flow, as packets or bursts belonging to existing data flows may also be dropped/delayed due to traffic surge. Obviously, one cannot simply compare the request blocking rate in an OCS network with the packet/burst loss rate in an OPS/OBS network to arrive at any meaningful conclusion.

Intuitively, a WDM network with fast switches should be more resource efficient than the one without (note that, interestingly enough, one previous study which we believe was based on a questionable model had shown otherwise [2]). However, given the above stated difficulties (and controversy), it is not surprising that there is no prior work that can convincingly show that the former can provide the same bandwidth guarantee service as the latter and yet using less resources. Among a few previous attempts to compare OCS and OBS, the work in [3], which examined the packet-level loss/delay performance, came closest to achieving the goal of conducting a fair comparison but still falls short. This is because although in OBS, the overall packet loss probability was shown to be lower than that in OCS (given the same amount of resources), packets loss occurs in some data flows which in OCS will not experience any packet loss since wavelength circuits are provisioned for them in OCS.

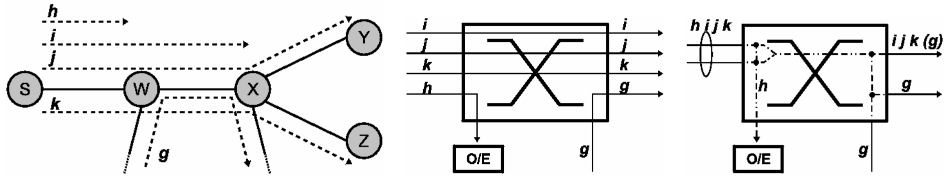
In the following, we show, for the first time, that by taking advantage of the fast switches, one can provide the same guaranteed bandwidth services as in OCS (and accordingly, identical QoS performance) while still exploiting the statistical multiplexing gains to achieve a higher resource efficiency.

2. Methods, models and results

We first describe a novel method which allows a WDM network with fast switches to provide the same guaranteed bandwidth as OCS while still taking advantage of statistical multiplexing gains. The proposed method, to be called LOBS-H (for Labelled OBS with Home circuits), emulates OCS but differs from OCS as well as from previous OCS-emulation approaches such as WR-OBS [4].

In LOBS-H, each source-destination pair (s, d) is first assigned a home circuit of a certain amount of bandwidth. As in OCS, the amount of bandwidth allocated to (the data flows of) the (s, d) pair is equal to the effective bandwidth (EB) required by the flows between (s, d). The amount of EB is determined in such a way that given the expected traffic load, required QoS (including zero loss and small delay) can be achieved with EB for in-profile traffic. Once the amount of the bandwidth is determined, a wavelength (or wavelengths) are allocated to the home circuit, and all protocol data units (PDUs) carried by the home circuit will be assigned a high (pre-emptive) priority. Unlike in OCS, two home circuits from the same source s to two different destinations d_1 and d_2 using the same route can share the same wavelength on the common links up to d_1 (which we assume is closer to s), without requiring the transit traffic to d_2 to go through OEO conversion for traffic grooming purposes.

Let us consider the example depicted in Fig.1(a), with four flows from node S: $h = (S, W), i = (S, X), j = (S, Y)$ and $k = (S, Z)$. Assume their required EB (normalized to the wavelength transmission capacity) are $A_h = A_i = A_j = A_k = 0.3$. In OCS, each flow uses an optical circuit which must be exclusively allocated $\lceil 0.3 \rceil = 1$ wavelengths on every traversed link. Two circuits such as j and k cannot share the same wavelength, since transit traffic should not go through OEO and every switch (including the one at node X) is wavelength-routed. Thus, the number of wavelengths needed on each link is as follows: $\lceil A_h \rceil + \lceil A_i \rceil + \lceil A_j \rceil + \lceil A_k \rceil = 4$ on link S–W, $\lceil A_i \rceil + \lceil A_j \rceil + \lceil A_k \rceil = 3$ on link W–X, $\lceil A_j \rceil = 1$ on X–Y, and $\lceil A_k \rceil = 1$ on X–Z.



(a) (b) (c)

Fig. 1. Example topology (a) with four flows (h, i, j and k) from node S, and one transit flow (g) trough nodes W and X (whose source and destination are not shown). Operation of node W with OCS (b) and LOBS-H (c) is also shown.

In LOBS-H, the home circuits for the same source can share the same wavelength on common links, and thus, the number of wavelengths used on each link is: $\lceil A_h + A_i + A_j + A_k \rceil = 2$ on S–W, $\lceil A_i + A_j + A_k \rceil = 1$ on W–X, $\lceil A_j \rceil = 1$ on X–Y, and $\lceil A_k \rceil = 1$ on X–Z. This is doable as (i) the common sources can automatically resolve collisions among PDUs from different flows for the same wavelength by sending the PDUs out sequentially, and (ii) each fast switch can switch one PDU at a time, i.e., on a PDU-by-PDU basis, and accordingly (de)multiplexes PDUs from different flows in the optical domain without unnecessary OEO conversions. We note that in LOBS-H, the wavelengths assigned to home circuits can also be used by out-of-profile traffic from *any* source to *any* destination, and doing so will not affect the guaranteed bandwidth services as long as those PDUs are assigned a lower priority. For example, refer to Fig.1(a), out-of-profile traffic belonging to flow g (which has one wavelength reserved on W–X for the in-profile traffic), in the form of PDUs, can be switched at node W onto the wavelength assigned to flows i, j and k (and later exiting at node X), as long as there is no traffic on the wavelength at the time of switching, thanks to fast, PDU-by-PDU switching at node W. Such is not possible with a wavelength switch (and OCS). The figures also illustrate the main differences between a wavelength-routed switch (Fig.1(b)) and a fast switch (Fig.1(c)).

In short, LOBS-H differs from classic OBS in that the former provisions home circuits based on EB, and allocates wavelength(s) to them to provide guaranteed bandwidth services. LOBS-H also differs from WR-OBS and OCS in that the former, by taking advantage of fast switching, allows home circuits from the same source to different destinations to share the wavelengths (through statistical multiplexing of their PDUs) to achieve high resource efficiency. Additional features (and benefits) of LOBS-H include allowing non-home-circuit traffic (i.e., out-of-profile traffic from any source to any destination) to utilize the available bandwidth allocated to a home circuit to further increase statistical multiplexing gains without sacrificing bandwidth guarantee to in-profile traffic.

3. Performance evaluation

We have studied and compared OCS and LOBS-H through both analysis and simulation experiments. The scenario of study is the well-known NSFNET topology (14 nodes and 42 unidirectional links), with identical traffic flows between every source-destination node pair. The routes employed are the shortest ones. Wavelengths operate at 10 Gbps. Traffic is Poisson and the packet/burst size is exponentially distributed, with mean value 500 Kbytes (since the focus is on the effect of fast switching, the effect of burst assembly in LOBS-H is not studied, and we assume that the burst arrival process in LOBS-H and the packet arrival process in OCS are identical). Full wavelength conversion is available.

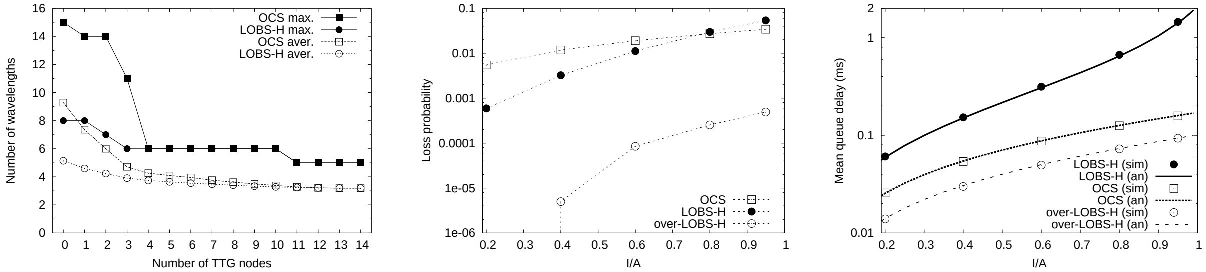
Fig.2(a) shows the average number of wavelengths per link, and the maximum number of wavelengths (i.e., on the link with most wavelengths), needed with both LOBS-H and OCS, as a function of the number of transit traffic grooming capable (TTG) core nodes, when the EB required by each source-destination flow is $A = 0.3$ (normalized to the wavelength transmission capacity). We assume that in a TTG node, the traffic grooming capability will always be sufficient for handling all the traffic that traverses it. Given a number n of TTG nodes, we choose the combination of n TTG nodes which minimizes the average number of wavelengths per link (by probing every possible combination of

n nodes, which takes polynomial time). As expected, in both LOBS-H and OCS, the number of required wavelengths decreases with the number of TTG nodes. It can be seen that OCS needs significantly more wavelengths per link than LOBS-H, due to the coarse granularity of the bandwidth reservation. In fact, even with no TTG nodes, the resource utilization with LOBS-H is almost as good as that with every node being TTG.

We have studied the loss and delay performance with OCS and LOBS-H. We consider a network dimensioned for $A = 0.3$ without TTG nodes. Note that for OCS, the network will be dimensioned with more resources than that for LOBS-H. Thus, we have also studied LOBS-H *with overprovisioning* (*over-LOBS-H*), i.e., in the same network as OCS, so that the home circuits can use as many wavelengths as the OCS circuits and the comparison with OCS is fair.

Given the delay constraints, $D_{\max}$ is the maximum queue delay, that is, the maximum amount of time that a packet/burst can be at the source node waiting for a wavelength being available to be sent on. If a flow occasionally sends more traffic than the bandwidth initially requested, $D_{\max}$ may be exceeded by part of the traffic, resulting in data loss; as explained in Section 2, OCS would drop this out-of-profile traffic, while LOBS-H would try to send it with low priority out of the home circuit. Fig.2(b) depicts the data loss probability obtained through simulation with $D_{\max} = 1$ ms, as a function of I/A, where I is the mean offered traffic per flow. The higher I/A is, the higher the losses are. It can be seen that, although the network of OCS has more resources than that of LOBS-H, LOBS-H suffers significantly less losses than OCS, except for high values of I/A. When both of them employ the same amount of resources, the data loss rate with LOBS-H (i.e., over-LOBS-H) is several orders of magnitude lower than that with OCS.

Fig.2(c) depicts the average queue delay as a function of I/A assuming that traffic do not have delay constraints ($D_{\max} = \infty$). Results were obtained through both analysis and simulations. The analysis is based on considering each link an M/M/C system. For OCS, the analysis is trivial. In the case of LOBS-H, as a simple approximation, the analysis assumes that the queue delay of a flow is solely determined by the bottleneck link. The analysis has shown to be accurate for both OCS and LOBS-H. The higher I/A is, the higher the queue delay is. Since its network has more resources, OCS obtains lower queue delay than LOBS-H. However, over-LOBS-H suffers significantly lower queue delay than OCS, thanks to its statistical multiplexing capability. Thus, the results confirm that, when both of them employ the same amount of resources, LOBS-H can perform much better than OCS.



(a) (b) (c)

Fig. 2. (a) Average and maximum number of wavelengths per link as a function of the number of TTG nodes with $A = 0.3$. Data loss probability (b) and mean queue delay (c) with OCS and LOBS-H (including over-LOBS-H) as a function of I/A with $A = 0.3$.

4. Concluding remarks

We believe that the today's immaturity and slow development of fast optical switching fabrics is partially due to the fact that it is a challenging task to show the benefit of fast switching in WDM networks to convince carriers and vendors. In this work, we have developed a novel method called LOBS-H to provide guaranteed bandwidth services as in OCS, while taking advantage of fast switching to achieve statistical multiplexing gains and high resource efficiency. Through both analysis and simulations, we have demonstrated the benefit of fast switching in WDM optical networks. We hope that our work will stimulate the research and development of fast optical switching fabrics.

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