A Framework to Support IP over WDM Using Optical Burst Switching *

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Abstract

Optical burst switching (OBS) has been proposed as a switching technique to exploit enormous amount of capacity provided by wavelength division multiplexing (WDM) transmission technology. In this paper, we consider a model for overlaying IP network over the OBS WDM transmission backbone. In the framework of this model, the functional requirements of the interface between the IP layer and the OBS WDM layer are pointed out. Aimed at achieving some of these functionalities, we propose a scheme to set the "offset," an important system parameter for OBS, between the successive data bursts and their control packets. It is based on the systematic randomization of the time instances of releasing data bursts into the optical network to provide a reliable transport service to IP layer by keeping a low value of burst blocking probability. The role of this scheme in improving the performance of OBS is demonstrated via simulations for the case of TCP/IP traffic.

Keywords: Optical burst switching, WDM, TCP/IP, MPLS, quality of service, traffic shaping.

1 Introduction

Spectacular growth in the Internet traffic in the last decade has triggered much interest in devising new high-speed transmission and switching technologies [16, 3, 10, 2, 7, 20]. Of particular importance has been the emergence of "wavelength division multiplexing" (WDM) [3], which can support a number of simultaneous Gigabit channels in a single optical fiber. This provides enormous bandwidth at the physical layer. In order to exploit this bandwidth to meet the future data traffic requirements, it is essential to develop higher layer communication protocols which would enable the applications to make efficient use of the underlying transmission capacity.

The present WDM deployment is mostly point-to-point, and uses SONET/SDH as the standard layer for interfacing to the higher layers of the protocol stack. The IP routers/ATM switches in such a backbone still use electronic processing. Electronic processing involves header processing for routing (such as table lookups or label swapping) and also involves processing for data multiplexing (for example, IP packets may be mapped into ATM cells before transporting over WDM using SONET frames). Although there has been dramatic increase in the speed of electronic devices in the recent past, it is not likely to catch up with the transmission speed provided by the WDM layer. Such an electronic bottleneck makes it difficult to use WDM

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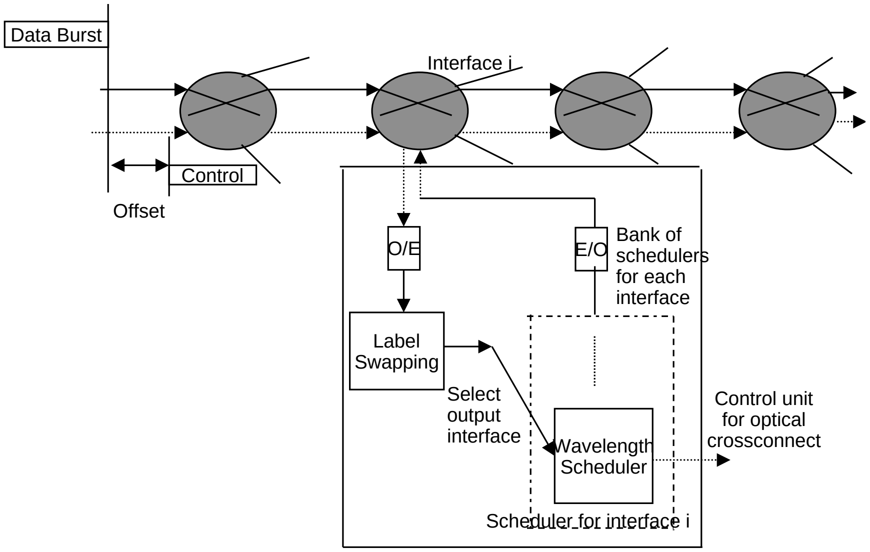

Figure 1: Optical burst switching

bandwidth to its fullest potential [5]. This necessitates the elimination of optics-electronics-optics conversion at the intermediate nodes in the end-to-end data path.

Ideally, one would like to deploy an all-optical packet switch eliminating the electronics altogether. However, due to a number of technological constraints such as limited optical buffering (implemented presently using optical delay lines) that can store only a few packets or difficulty in switching light pulses using light as control, optical packet switching is still in the experimental stage [11, 21].

As a viable alternative to all-optical packet switches, optical burst switching (OBS) has been proposed [9, 18]. OBS allows switching of data channels entirely in the optical domain by doing resource allocation in the electronic domain. In OBS, a control packet precedes every data burst. The control packet and the corresponding data burst are launched at the source at time instants separated by an “offset”. The offset is determined at the time the control packet is launched at the source. The control packet contains the information required to route the data burst through the network, and also contains the length of the corresponding data burst and the offset value. The control packet is sent over an out of band channel (wavelength). This control packet is processed electronically at each of the intermediate nodes to make routing decisions (outgoing interface and wavelength), and the switching fabric at each node is configured accordingly to switch the data burst that is expected to arrive after a time interval given by the offset field in the control packet. The impending data burst is then switched entirely optically thereby removing the electronic bottleneck in the end-to-end data path. This is shown pictorially in Figure 1. However, there are a number of design issues related to the efficient implementation of this switching technique. One of them is the determination of offsets for successive data bursts. The value of offset should be large enough to allow for electronic processing of control message at intermediate nodes. Also, there is a need to minimize the contention among bursts coming from different (possibly geographically dispersed) sources. Some other issues are the selection of appropriate wavelength at the switch output interface to route the data burst [8, 6, 12, 4, 1, 15, 14], and the determination of burst size. A large value of burst size is desirable since, roughly, data transmission can occur at a rate equal to the electronic bottleneck speed multiplied by the ratio burst size to the size of the control packet.On the other hand a small value of burst size may be required to reduce burst assembly delay for delay sensitive applications.

This paper addresses the first of these issues. We propose a shaping scheme to determine the offsets of successive data bursts from their control packets. This scheme is based on the systematic randomization of the time instances of releasing data bursts into the OBS WDM network. It maintains the end-to-end burst blocking probability in the networkwide-contention-prone OBS WDM backbone to the pre-engineered

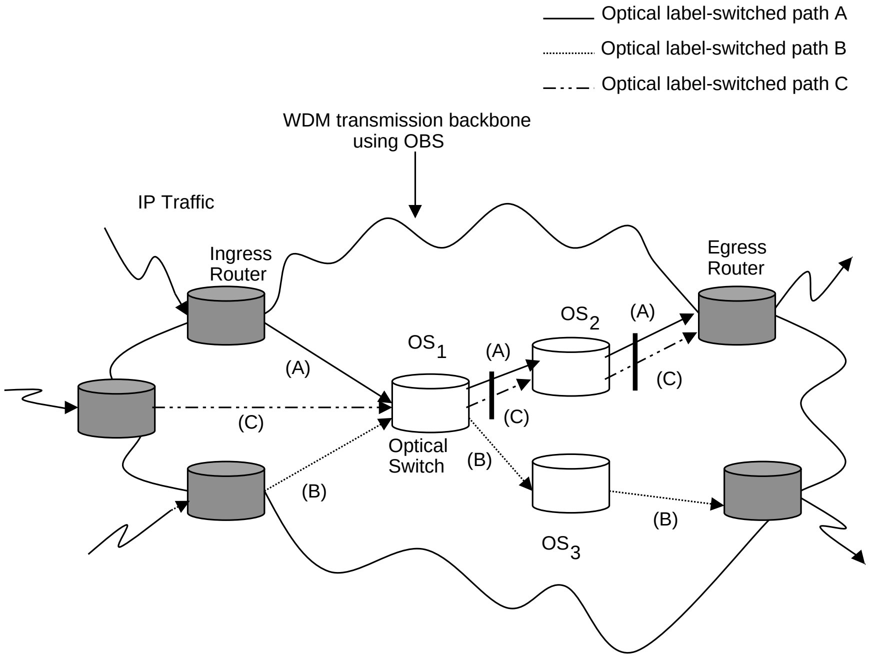

Figure 2: IP over OBS WDM transmission backbone using OMPLS.

(small) value resulting in its reliable operation. The proposed shaping scheme also provides a tractable handle for resource provisioning and connection admission control at the nodes in the OBS WDM backbone. The effectiveness of this scheme in improving the performance of OBS is then demonstrated through simulations for the case of TCP/IP traffic.

The paper is organized as follows. Section 2 describes the system model and the role of OBS WDM in the emerging Internet backbone model. In Section 3, we describe the shaping scheme proposed in this paper. Guidelines for using the proposed shaping scheme for robust network provisioning are provided in Section 4. Section 5 gives the details of the simulation model used to test the performance of the proposed scheme, and also contains numerical results from the simulation. We close with conclusions and directions for future research in Section 6.

2 System Model

We envision an IP (Internet Protocol) network operating over OBS WDM transmission backbone as shown in Figure 2. There are IP routers at the ingress and the egress of the network, and the intermediate nodes employ OBS. Data bursts are assembled at the ingress and then delivered to the egress in all-optical domain. We assume that there is no buffering of data bursts at the intermediate nodes. Semi-permanent data pipes can be set up between different ingress-egress pairs using, say, "multiprotocol label switching" (MPLS) [1]

2.1 MPLS for OBS and sub-wavelength allocation

IP routing and forwarding engine presents a major bottleneck at Terabit speeds, due to its processing requirement. MPLS is [2] a forwarding technique that uses the labels associated with packets to make packet forwarding decisions at the network nodes, in contrast to the conventional destination-based hop-by-hop forwarding. In MPLS, the space of all possible forwarding options is partitioned into "forwarding equivalence classes" (FEC's). For example, all the packets destined for a given egress node, and having the

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[1] Note that the approach here differs from that of [17] in that the latter is based on circuit switching paradigm.

same quality of service requirement may belong to the same FEC. The packets are labeled at the ingress depending on the FEC to which they belong. Each of the intermediate nodes uses the label of incoming packet to determine its next hop, and also performs "label swapping," i.e., replaces the incoming label with the new outgoing label that identifies the respective FEC for the downstream node. [2] Such a label-based forwarding technique reduces the processing overhead required for routing at the intermediate nodes, improving their packet forwarding performance and scalability. Also, the label swapping process used by MPLS creates multipoint-to-point routing trees in contrast to a routing mesh in conventional networks based on similar forwarding paradigm such as ATM networks. Another important capability that MPLS provides is that of "constraint-based routing". The ingress node can establish an explicit route through the network. [3] Rather than inefficiently carrying the explicit route in each packet as in datagram routing, MPLS allows the explicit route to be carried only at the time the "label switched path" (LSP) is set up. The subsequent packets traversing this path are forwarded using packet labels. Constraint-based routing is potentially useful for traffic engineering.

MPLS-type mechanisms can be used for routing in OBS WDM domain as well. As a starting point, it can be seen that the control packet can simply carry label in addition to the offset and burst length information. The label can be thought of as encoding the relevant information about the "connection." Specifically, the label can point to the information about (i) route of the connection, thus specifying the input-interface to output-interface mapping, and (ii) any priority or QoS information about the connection. Essentially, each optical node running this "optical MPLS" (OMPLS) will have a "label information base" or LIB (just as in the conventional MPLS) which stores the characteristics of the label. Hence, when the labeled control packet arrives at a node, the LIB can be looked up to determine the information about the connection including the routing information.

We refer to this type of use of the optical layer as "sub-wavelength allocation." This is because, here the allocations to connections can be less than a wavelength, i.e., upon a particular request (control packet), allocation of wavelength is only for the duration of the burst, and bursts from different connections share the wavelength. Alternately, this may be seen as establishment of virtual connections over the optical network. We call them "optical LSP's."

2.2 MAC interface between IP and OBS WDM layers

We assume that there is a "medium access control" (MAC) interface between the IP layer and the OBS WDM layer. The MAC layer is responsible for assembling data bursts from the packets generated by IP layer for each optical LSP. Various QoS mechanisms (e.g. DiffServ) can be used at the IP layer before the packets are released to the MAC layer. We require that an optical LSP appears to IP layer as a reliable data pipe that guarantees certain (low) burst blocking probability (see Figure 3). Devising MAC layer functionalities to achieve this *reliability* is the main subject of this paper.

2.2.1 Data loss due to burst blocking

Note that an output interface (fiber) of a node in the OBS WDM domain receives traffic from different optical LSP's. For example, in Figure 2, the output interfaces of the optical nodes OS1 and OS2 receive traffic from optical LSP's A and C. This creates the potential for contention among different LSP's. When the control packets from different LSP's request reservations for their data bursts on a particular wavelength of a given output interface for the time intervals that overlap with each other (henceforth referred to as "burst blocking"), only one of these requests can be granted. Then, some control packets have to be dropped at that interface. This, in turn, results in the loss of data bursts corresponding to the dropped control packets. Data loss rate due to burst blocking will be large if the reservation requests arriving at a given output interface from different optical LSP's are correlated. Further, due to unpredictable nature of traffic, it is difficult to always guarantee low burst blocking probability.

In this paper, we propose a shaping mechanism, to be incorporated in the MAC layer at the ingress, that facilitates the determination of offsets for the successive data bursts, so that a low burst blocking probability is

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[2] Note that labels have only local significance, while FEC's are globally identified.

[3] Explicit routing is a special case of constraint-based routing.

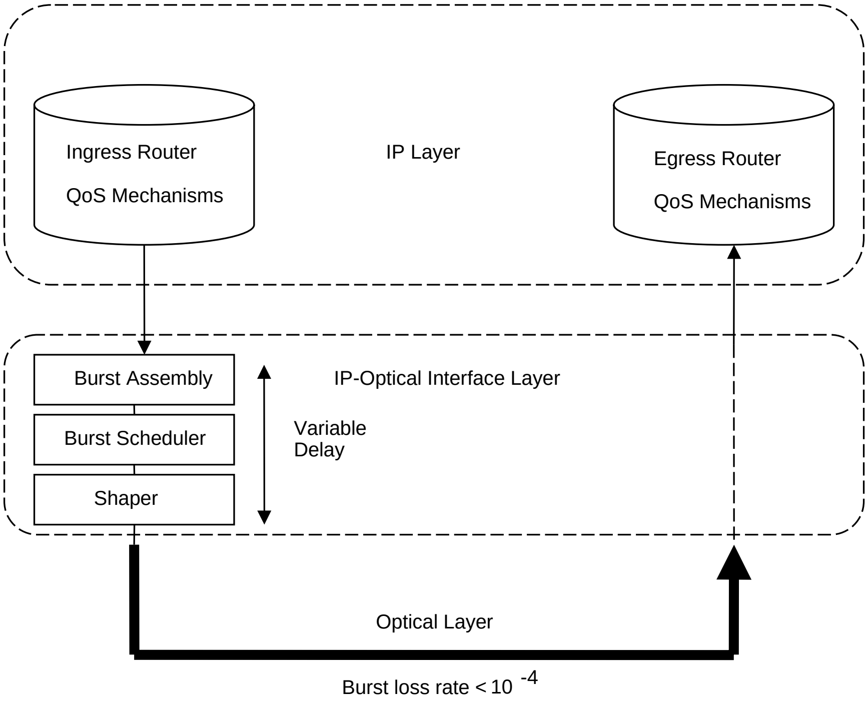


Figure 3: MAC interface between IP and OBS WDM layers

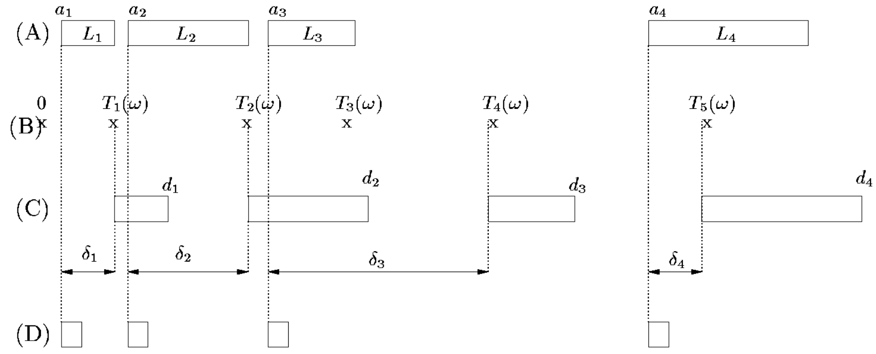
maintained in the OBS WDM layer at all times. The proposed shaping scheme aims at breaking pro-actively, the correlation among the reservation requests of different optical LSP's. It also enforces the predetermined statistics on the data burst stream entering into the OBS WDM layer, irrespective of the statistics of the packet stream generated by the IP layer that resides over it. This statistics is invariant even if the burst stream traverses multiple nodes in the OBS WDM domain. Knowledge of the statistics of burst arrivals at different nodes in OBS WDM layer provides a handle on resource provisioning and admission control at the nodes in OBS WDM domain.

3 Burst Stream Shaping and Determination of Offsets

As shown in Figure 3, the stream of data bursts to be sent over a particular optical LSP is first offered to the shaper. For every data burst in this stream, the shaper determines the value of the offset to be maintained between it and the control packet that would precede it. It then forms the control packet, and sends it over the control channel. The control packet contains information such as the offset value, the length of the data burst, and the information (label) required for routing. Data burst is released by shaper into the OBS WDM layer after the control packet is sent, separated from the latter by time duration equal to the calculated offset.

The offset assigned to any data burst consists of two parts: a constant part ϵ to account for the processing time of the control packet at the intermediate nodes, and a variable part, i.e., the part that varies from burst to burst. Let the variable part of the offset for the i th data burst be denoted by δ_i. It is determined as follows.

Let $T_0 = 0$, T_1, T_2, $\cdots$ denote the times of occurrences of points of a random point process in which the time periods between the occurrences of successive points (i.e., $T_i - T_{i-1}$, for $i \geq 1$) are independently and identically distributed according to probability distribution $F(\cdot)$. Let $T_0(\omega) = 0$, $T_1(\omega)$, $T_2(\omega)$, $\cdots$ denote a particular realization (sample path) of this random point process. Suppose that the i th data burst arrives at the shaper at time a_i, and that δ_{i-1} is determined with respect to $T_{k_{i-1}}(\omega)$. Then, δ_i is determined with



(A) Data bursts before shaping
(B) Token arrivals
(C) Data bursts after shaping
(D) Control packets

Figure 4: Data burst shaping

reference to $T_{k_i}(\omega)$, where $T_{k_i}(\omega)$ is the first point after $T_{k_{i-1}}(\omega)$ satisfying the following.

$$T_{k_i}(\omega) - T_{k_{i-1}}(\omega) \geq L_{i-1} \text{ and } T_{k_i}(\omega) \geq a_i.$$

Here, L_{i-1} denotes the length of the $(i-1)$ th data burst. Then, the variable part of the offset for the i th data burst would be,

$$\delta_i = T_{k_i}(\omega) - a_i,$$

and the overall offset between the i th data burst and the control packet corresponding to it would be $\delta_i + \epsilon$. This is shown in Figure 4. The shaping scheme described above is equivalent to leaky bucket regulator with *no* buffering provided for tokens, and in which tokens arrive at $T_0(\omega)$, $T_1(\omega)$, $T_2(\omega)$, $\cdots$.

This type of shaping achieves many desirable objectives, as given below.

- It regulates the average rate at which data bursts are released into the OBS WDM layer. This rate is given by the reciprocal of the mean of the probability distribution $F(\cdot)$ that is used to generate tokens.
- Randomized generation of tokens prevents any systematic synchronization among the token streams of different optical LSP's. This is necessary because, if the token generators of two optical LSP's traversing the same output interface of some node in the OBS WDM network happen to be synchronized, the data bursts in these LSP's will almost always collide with each other at that interface causing excessive loss. The random generators for tokens at different hosts can be initialized with, say, host-address-specific seeds, so that they never get in systematic synchronization.
- The proposed shaping scheme also imposes the following property on the stream of data bursts of any optical LSP. Let $\{A(t)\}_{t\geq 0}$ denote total data arriving over an optical LSP till time t at *any* node (ingress or intermediate) in the OBS WDM network. Then,

  $$A(t) - A(s) \leq A_X(t) - A_X(s), \text{ a.s. (almost surely), for all } t \geq s, \quad (1)$$

  where $\{A_X(t)\}_{t\geq 0}$ denotes total data that would arrive on that optical LSP till time t at that node, if data bursts were arriving at T_0, T_1, T_2, $\cdots$.

  It is easy to see that the domination as in Eq. (1) holds at the output of the shaper of every optical LSP, by virtue of the shaping scheme. As data bursts traverse various nodes in the optical backbone, some of them can *only be discarded*, due to contention. Further, due to inherently bufferless forwarding, the relative positions of the data bursts of any optical LSP remain unchanged even after these data bursts traverse a number of nodes. Hence, the domination as in Eq. (1) holds at the output interface of every node that a given optical LSP traverses.

A framework for traffic engineering, based on the above shaping scheme, is given in the next Section. The role of this shaping scheme in improving the performance of OBS WDM layer is demonstrated in Section 5 for the case of TCP/IP traffic.

4 Traffic Engineering in the Optical Backbone

Consider an output interface (fiber) of any node in OBS WDM network. Suppose that this node is being traversed by N data pipes (optical LSP's) with the provisioned data rates of $r_1, \cdots, r_N$, respectively. If the data bursts entering into these optical LSP's are shaped at the ingress using Poisson shapers (this means that the probability distribution for the time interval between the successive tokens of the i th optical LSP, denoted by $F_i(\cdot)$, is chosen to be exponential), the following holds for their data arriving at the output interface under consideration. For all $t \geq s$ and $1 \leq i \leq N$,

$$A_i(t) - A_i(s) \leq A_{P(r_i)}(t) - A_{P(r_i)}(s), \text{ a.s., and} \tag{2}$$

$$A(t) - A(s) = \sum_{i=1}^{N} (A_i(t) - A_i(s)) \leq A_{P(r)}(t) - A_{P(r)}(s), \text{ a.s.} \tag{3}$$

Here, $A_i(t)$ denotes the total data arriving over the i th optical LSP till time t, $A_{P(x)}(t)$ denotes the data that would arrive if data bursts were arriving according to Poisson process of rate x, and $r = \sum_{i=1}^{N} r_i$.

Now, if $p_{\text{actual}}(r_1, \cdots, r_N)$ denotes the actual burst blocking probability at the given output interface, it is intuitively appealing to say that

$$p_{\text{actual}}(r_1, \cdots, r_N) \leq p_{\text{Poisson}}(r), \tag{4}$$

where $p_{\text{Poisson}}(r)$ denotes the burst blocking probability at that interface if the bursts were arriving according to the Poisson process of rate r. The right hand side of Inequality 4 is given by the well known Erlang loss formula [13, pp. 256],

$$p_{\text{Poisson}}(r) = \frac{(r/\mu)^c/c!}{\sum_{i=0}^{c} (r/\mu)^c/c!}, \tag{5}$$

where c is the total number of wavelengths at the output interface, and $1/\mu$ is the average burst length.

The requests for the establishment of new optical LSPs can be processed by using following admission control mechanism. If the establishment of a new optical LSP, requiring data rate of r_{N+1} and burst blocking probability of p_{N+1}, is requested through a given output interface at a node in OBS WDM network, it can be admitted if and only if

$$p_{\text{Poisson}}(r) \leq p_{N+1}, \text{ with } r = \sum_{i=1}^{N+1} r_i \tag{6}$$

5 Performance of TCP/IP over OBS WDM with and without Burst Stream Shaping

We simulate the bottleneck output interface (fiber) of a node in OBS WDM network supporting three OC12 wavelengths (622 Mb/s per wavelength) per output interface. This interface is traversed by a number of optical LSP's. We simulate 10 such optical LSP's each carrying ingress-to-egress data traffic supported on TCP/IP. There are (forward paths of) 4 TCP (Reno) sessions in each of these optical LSP's. The

Simulation experiment	Throughput (Mb/s)			Burst blocking probability		
	With shaping		Without shaping	With shaping		Without shaping
	Observed	Designed		Observed	Designed	
1	302.29	311.00	10.64	0.73×10^{-2}	1.27×10^{-2}	1.57×10^{-1}
2	146.68	155.00	29.05	1.17×10^{-3}	2.00×10^{-3}	0.97×10^{-1}
3	62.20	62.20	26.97	0.7×10^{-4}	1.51×10^{-4}	0.93×10^{-1}

Table 1: Numerical results

acknowledgment paths (or reverse paths) of these TCP's are taken to be lossless, and they introduce only a constant delay. Simulations are run with the OPNET simulation tool.

Each of the 40 TCP sessions is started at time instant sampled from the uniform distribution over [0 s, 1 s). Once started, all TCP sources always have data to send. For simplicity, every data burst that is assembled at the MAC layer is taken to be precisely one IP packet. The delay introduced by the reverse path of every TCP session is sampled from the uniform distribution as explained in the next section.

As shown in Figure 3, the burst traffic offered to each optical LSP is shaped at the ingress. The probability distribution $F_i(\cdot)$ used in shaping the burst traffic of the i th optical LSP is taken to be exponential with mean $1/r_i$. This causes the data burst arrivals at the output of each shaper to be dominated by the Poisson process of rate r_i, and the total arrival process of data bursts at the bottleneck output interface to be dominated by the Poisson process of rate $r = \sum_{i=1}^{10} r_i$. Simple greedy and exhaustive wavelength selection policy is used to assign reservations to control packets arriving at the bottleneck output interface.

Simulation experiments are run in different regimes of the target burst blocking probability, namely, 10^{-2}, 10^{-3} and 10^{-4}. For each of these values, the total allowable load r at that output interface is calculated using Erlang loss formula (Eq. (5)), with $c = 3$. r_i is then taken to be $r/10$, for $i = 1, \cdots, 10$. For the target burst blocking probabilities of 10^{-2}, 10^{-3} and 10^{-4}, the delay introduced by the reverse path of every TCP session is sampled from the uniform distribution over [0 ms, 1 ms), [0 ms, 25 ms) and [0 ms, 50 ms), respectively. This is done so that the actual aggregate load offered by all TCP's is not much lower than the designed throughput value. For example, 40 TCP's fail to offer average load as large as about 311 Mb/s at the packet loss probability of 10^{-2} in the end-to-end path, if their round trip times are larger than about 1 ms.[4] And, it is clearly trivial to establish Inequality 4 if the offered average load itself is much lower than the designed value for the load. Simulations are run long enough to achieve the confidence interval of less than 10 % of the corresponding burst blocking probability.

6 Discussion

In this paper, we introduced a framework for robust transport of IP traffic and implementation of related QoS mechanisms, over WDM transmission backbone using optical burst switching. This proposal has two main components. The first component is the logical partitioning of the optical backbone by establishing semi-permanent data pipes (optical LSP's) between different ingress-egress router pairs using MPLS-type technology in the optical domain. The other component is the inclusion of MAC layer functionalities to render certain characteristics to these optical LSP's. For the latter, we proposed a novel shaping and offset-setting scheme that offers reliable transport service in the WDM OBS backbone (in terms of low burst blocking probability) to IP layer.

Simulations were run for the case of transport of TCP/IP traffic over the optical backbone. Results from simulations show that it is possible to provide reliable transport service at the optical layer using the proposed shaping scheme. Further, the burst blocking probability observed in simulations was found to be less than and close to the engineered value, thereby justifying the approach advocated in this paper. The

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[4] It is a fundamental fact about TCP (see [19]) that TCP throughput significantly deteriorates if the end-to-end packet loss probability is much larger that the inverse square of the product of bottleneck bandwidth and round-trip delay.

results also show marked improvement due to shaping in the throughput and the burst blocking performance over the case when no such mechanism is deployed.

There are a number of design issues that are not addressed in this paper and are subject of further investigation. Some of them are studying burst assembly and scheduling algorithms in the MAC layer, and wavelength selection mechanisms at the output interfaces of optical nodes. There is a need to introduce mechanisms (such as "label distribution protocol" (LDP) in the conventional MPLS) to establish optical LSP's across the OBS WDM backbone. It will also be interesting to analyze the performance of the proposed shaping scheme under different statistics for token generation.

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