A hybrid optical network architecture consisting of optical cross connects and optical burst switches

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Keywords
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A hybrid optical network architecture consisting of optical cross connects and optical burst switches

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Abstract—Optical burst switches (OBSes) have been proposed to improve the utilization of a network of optical cross connect (OXC). Current studies on OBS assume a network consisting of OBSes alone. While this is a reasonable assumption for evaluating a new technology, the question of how a network of OXCs can be evolved to a network of OBSes has not been studied. In this paper, we propose a hybrid architecture consisting of OBSes at the network edge and OXCs in the network core. This architecture allows carriers to gradually migrate from an OXC-based network to an OBS-based network with an improved network utilization. In addition, we use queueing analysis to study the performance of this new architecture.

Keywords: Optical burst switches, Optical network architecture, Optical cross-connects, Performance Evaluation, Queueing analysis

I. INTRODUCTION

The development of wavelength division multiplexing (WDM) has allowed us to exploit the large amount of bandwidth available in an optical fiber as multiple lower-capacity channels. With the introduction of Optical Cross-connects (OXC), end-to-end optical connections (also known as lightpaths) allow packets to be carried without optical-to-electronic conversion in the intermediate hops, thus overcoming the electronic conversion bottleneck. However, due to the static nature of these lightpaths and the burstiness of IP traffic, the utilization of an OXC-based network can be low. A proposed solution to this problem is to deploy optical burst switches (OBSes) [Tur99], [YQ99], [Qia00].

OBS can be viewed as fast wavelength switching where the holding time of a wavelength is in the order of an optical burst. (The precise wavelength holding time depends on the reservation protocol being used). An important feature of OBS is the separation of control and data. A control packet is sent over a separate control channel ahead of the optical burst to perform channel reservation. Since no optical buffer is used, if the number of arriving bursts exceeds the number of optical channels available, the excess bursts will be dropped. An important performance metric of OBS is therefore burst blocking probability.

Current research on OBS focuses on a number of areas, which include OBS network architecture [Tur99], [YQ99], [XVC00], [DB02], resource allocation and reservation mechanisms [DGSB01], burst aggregation mechanisms [OK02], burst shaping [CVR02], Quality of Service (QoS) support [YQD01], labeled switched OBS [Qia00], performance of TCP over OBS [DL02] and many others. All of these studies assume a network consisting of OBSes alone. While this is a reasonable assumption in evaluating a new technology, one needs to realize migrating from a network of OXCs to a network of OBSes is a large capital investment. It is therefore important to be able to incrementally deploy a new technology such as OBS. In this paper, we propose a hybrid optical network architecture which consists of OBSes at the network edge and OXC in the network core. This architecture provides an incremental migration path from a pure OXC network to a pure OBS network. We will describe this hybrid architecture in details in section II. In section III, we use queueing analysis to derive an upper bound on the blocking probability for this hybrid architecture. Finally, the conclusions are given in section IV.

II. HYBRID OPTICAL NETWORK ARCHITECTURE

The aim of this section is to present an optical network architecture which allows a carrier to migrate from an OXC-based network to an OBS-based network. In order to put the discussion in context, we first describe the current OXC-based architecture, which is depicted in Figure 1. This architecture consists of IP routers, edge OXC nodes and core OXC nodes. An end-to-end optical channel, or lightpath, is set up between a pair of IP routers so that traffic can be exchanged between them. The lightpaths are switched in the optical domain in the OXCs without converting into electronic signals. It is instructive to point out that even if a router is to send traffic to two different routers that are attached to the same edge OXC, two different lightpaths are required. For example, in Figure 1, three different lightpaths are used to transport the traffic from routers a, b and c to router d even routers a, b and c are all connected to the same OXC.

Note that multiple lightpaths may be set up between a pair of IP routers if there is sufficient traffic demand. Lightpaths are currently set up manually (thought research is being done in establishing these lightpaths dynamically [ZJS01]) and are therefore static in nature. The network utilization of an OXC-based network is generally low due to static lightpaths and burstiness of IP traffic.

A. Hybrid optical network architecture

In this section, we present a hybrid optical network architecture which consists of both OXCs and OBSes to facilitate
the migration from an OXC-based network to an OBS-based architecture. The proposed architecture is depicted in Figure 2, it consists of IP routers, OBSes at the network edge and OXCs in the network core. This new architecture is best understood by describing the differences between it and the OXC architecture given in Figure 1, as follows.

1) Burst assembly mechanisms are added to the IP router ports to facilitate burst creation. Note that [XVC00] also suggests to install burst assembly mechanisms in the IP router ports in their proposed OBS-based network architecture.

2) In the OXC based architecture, each wavelength between an IP router and an edge OXC carries traffic for only one IP router pair. However, a wavelength between an IP router and an edge OBS in the hybrid architecture can carry traffic destined for one or more IP routers. For example, for the OXC architecture, Figure 1 shows that the traffic from router a destined for routers d and e are carried in two separate wavelengths in the connection from IP router a to the edge OXC. However, in the hybrid architecture, Figure 2 shows that the same traffic is now carried over one wavelength from router a to OBS A. Note that OBS A will switch the incoming bursts to the appropriate wavelengths on its outputs. Note that this requires wavelength converters in the OBS. The number of wavelengths to be used between an IP router and an edge OBS depends on the amount of traffic to be carried but is expected to be no more than that required in the OXC-based architecture.

3) Lightpaths are organized differently in the two architectures. In the OXC architecture, a lightpath is established between an IP router pair and carries traffic between that particular IP router pair. However, in the hybrid architecture, lightpaths are established between a pair of edge OBSes to carry the traffic between them. For example, for the OXC architecture in Figure 1, the traffic from routers a, b and c that is destined for router d is carried over three different wavelengths, one for each router pair. However, in the hybrid architecture shown in Figure 2, the same traffic is carried in the core network over two wavelengths between OBSes A and C. OBS A therefore does the job of multiplexing the traffic from routers a, b and c that is destined for router d onto the two wavelengths between OBSes A and C.

The rationale behind the hybrid architecture is as follows: if r lightpaths are used to carry the traffic between an edge OXC pair in the OXC-based architecture (note that r is also the number of traffic sources between an edge OXC pair) and if the utilization of these lightpaths are low, the edge OBS can multiplex the same traffic onto m (< r) lightpaths between an OBS pair. For example, 3 wavelengths are used to carry traffic from routers a, b and c to router d in the OXC architecture in Figure 1 while two wavelengths are used to carry the same traffic between OBSes A and C in Figure 2. The hybrid architecture can therefore improve the utilization of the wavelengths in the optical core. For a carrier with an existing OXC-based network, this improved utilization in the optical core means that the migration to the hybrid architecture will allow it to carry more traffic using the existing network resources. The hybrid architecture therefore represents a viable intermediate architecture for migrating from an OXC-based network to an OBS-based network.

Note that if m < r, blocking of optical bursts may occur at the edge OBS (but not in the core OXC). Therefore, m should be chosen such that the blocking probability is sufficiently low and is an important input parameter to the Routing and Wavelength Assignment (RWA) problem associated with this hybrid architecture. Since m wavelengths are used to carry traffic between an edge OBS pair, it would be desirable to have all these m wavelengths routed along the same path in order to minimize the possibility of TCP packet reordering which results from using paths with large differences in propagation delay. This routing requirement can be incorporated in the RWA problem.

Some reader may argue that the improvement in utilization achieved in the hybrid architecture can also be obtained from using traffic grooming [ML01], [DR02] in the edge IP routers in the OXC architecture described above. This may well be the case. However, the purpose of this paper is to present a migration strategy from an OXC network to an OBS network, and traffic grooming does not provide such strategy.

A number of enhancements can be made to this architecture. If the underlying OXC network is equipped with dynamic lightpath establishment facility [ZJS01], the number of lightpaths between an edge OXC pair can be dynamically adjusted according to the aggregate traffic demands between and edge OBS pair. Alternatively, the edge OBS can monitor the burst dropping rate and adjusts the number of wavelengths being used accordingly.

It is also possible to introduce QoS into this architecture. For example, we can use multiple electronic buffers, one for each QoS service class, at the output ports of the IP routers. A strict priority queue or some scheduling algorithms can be used to differentiate the access to the shared wavelengths. Alternatively, QoS can be achieved by assigning different number of wavelengths to each service class.

An alternative design choice is to use two-way reservation, i.e., requests and acknowledgments, for the bursts to gain access to the wavelengths. The additional delay required will be small because the admission control decision will be made by the edge OBS to which the IP router is directly connected. No optical bursts will be blocked in this case but IP packets may be dropped due to buffer overflow. For an example of two-way reservation mechanism in OBSes, see [DB02].

III. PERFORMANCE ANALYSIS

In this section, we present analytical results on the performance of the proposed Hybrid Architecture. The general problem is described with the help of Figure 3 which shows an edge OBS X with r routers, which are the sources of optical bursts, connected to it. The bursts from these routers are destined for
all other edge OBSes in the network. Let OBS Y be another edge OBS and \( m \) be the number of wavelengths being used to carry bursts from OBS X to Y. The performance analysis problem can be stated as follows: given \( r, m \) and the traffic characteristics of the bursts (e.g. arrival rate, fraction of bursts destined for OBS Y etc.), compute the burst blocking probability for bursts destined for OBS Y.

A. Notation, assumptions and problem statement

The edge OBS nodes depicted in figure 3 are connected to a number of router ports which are the sources of optical bursts. A router port consists of an electronic-to-optical conversion unit and an electronic buffer. The role of the electronic buffer is to store the packets until they are ready to be converted into an optical burst. The electronic-to-optical conversion is done on a first-come-first-serve basis. This means that if an electronic-to-optical conversion is taking place while a group of packets is ready to be converted into optical domain, this group of packets will join a queue awaiting its turn to be converted. We define the arrival time of an optical burst as the time at which conversion begins (See the discussion below on the justification of this modelling assumption). These two times are identical if the electronic-to-optical conversion is idle when a burst is ready to be formed; otherwise, the difference between these two times is the queuing delay experienced by the burst. Figure 4 shows the burst arrival time as the time at which conversion begins. We assume the burst arrival time as the time at which a burst is ready to be converted without any delay or dropped. The key to arriving at the result is the observation that if no optical buffer is used at an OBS, a burst is either accepted without any delay or dropped.

In order to make the derivation easier to understand, we first show how an upper bound on blocking probability can be derived. The key to arriving at the result is the observation that if no optical buffer is used at an OBS, a burst is either accepted without any delay or dropped.

B. Upper bound on blocking probability with \( p = 1 \)

In this section, we derive an expression for the upper bound of burst blocking probability for the case \( p = 1 \).

**Lemma 1:** We consider the case where there are \( r \) router ports. At each router port, the bursts arrive according to Poisson distribution with mean \( \lambda \) and exponentially distributed service time with mean \( \frac{1}{\mu} \), where \( \mu > \lambda \). The arrival and service time distributions at all the ports are iid. Denote \( \rho = \frac{\lambda}{\mu} \).

Furthermore, all the optical bursts from these \( r \) router ports are destined for the same edge OBS and are served by \( m \) wavelengths. Let \( z_t \) denote the number of wavelengths that is busy at time \( t \). We have

\[
\text{Prob}(z_t = m) \leq \sum_{h=m}^{r} C_r^h \rho^h (1 - \rho)^{r-h} \tag{1}
\]

**Proof:** For the case where \( m > r \), i.e. there are more wavelengths than sources, \( \text{Prob}(z_t = m) \) is zero and equation (1) holds trivially.

For \( r \geq m \), we will first derive a lower bound for \( \text{Prob}(z_t \leq m-1) \) and use the fact that \( \text{Prob}(z_t = m) = 1 - \text{Prob}(z_t \leq m - 1) \) to obtain the upper bound given in equation (1).

Since no optical buffer is used at an OBS, a burst is either accepted without any delay or dropped. Therefore, a sufficient
condition for \( z_t \leq (m - 1) \) is that \((m - 1)\) or less sources are sending at time \( t \). This implies

\[
\text{Prob}(z_t \leq m - 1) \geq \sum_{h=0}^{m-1} C_h^r \rho^h (1 - \rho)^{r-h}
\]  

(2)

where the RHS of (2) gives the probability \( m - 1 \) or less sources are sending. Equation (1) is then obtained by using \( \text{Prob}(z_t = m) = 1 - \text{Prob}(z_t \leq m - 1) \).

**Proof:** We consider the case where there are \( r \) routers connected to a given edge OBS \( X \). At each router port, the bursts arrive according to Poisson distribution with mean rate \( \lambda \) and exponentially distributed service time with mean \( \frac{1}{\mu} \). The arrival and service time distributions at all the ports are iid. Let \( Y \) be another edge OBS. Each burst has an independent probability of \( p \) being destined for \( Y \) and altogether \( m \) wavelengths are used to serve the bursts destined for \( Y \). Denote \( \tilde{\rho} = \frac{p\lambda}{\mu} \). The blocking probability for those bursts destined for \( Y \) is bounded from above by

\[
(1 - \frac{m}{r}) \sum_{h=m}^{r} C_h^r \rho^h (1 - \tilde{\rho})^{r-h}
\]

(6)

An application of equation (6) is to compute the minimum number of wavelengths required to achieve a given blocking probability. Since equation (6) is a monotonically decreasing function in the integer variable \( m \), the minimum number of wavelengths required can be found readily by, for example, bisection search in \( m \).

**D. Numerical results and tightness of the bound**

We use simulation to study the quality of the upper bound given by equation (6). The simulation parameters are \( \frac{\lambda}{\mu} = 0.3 \) and \( r = 32 \). Figures 6 and 7 show how the blocking probability varies with the number of wavelengths for, respectively, \( p = 0.31 \) and \( p = 0.9 \). It can be seen that the upper bound is within an order of magnitude of the true blocking probability. In particular the upper bound is tighter for small blocking probability (e.g. \( 10^{-5} \)) which is the region of interest.

As mentioned earlier, an application of equation (6) is to compute the minimum number of wavelengths required to
achieve a given blocking probability. Figure 8 shows the number of wavelengths required to achieve a given blocking probability for $r = 32$ with $p = 1$. The utilization in the horizontal axis refers to the utilization of each source (which is itself an $M/M/1$ queue). It can be seen that the number of wavelengths required is significantly reduced. We have also used simulation to estimate the number of wavelengths required to achieve a blocking probability of $10^{-6}$ for source utilization of 0.1, 0.3, 0.5 and 0.7. The simulation predicts that we will require 14, 23, 29 and 32 wavelengths respectively in order to achieve the given blocking probability. The upper bound formula gives exactly the same number of required wavelengths and there appears to be a tight upper bound.

IV. CONCLUSIONS AND FUTURE WORKS

In this paper, we have proposed a hybrid architecture consisting of OBSes in the network edge and OXCs in the work core. In comparison with the OXC based architecture, hybrid architecture improves the utilization of the wavelength in the optical core. For a carrier with an existing OXC-based network, this improved utilization means that the migration to the hybrid architecture will allow it to carry more traffic using the existing infrastructure. The hybrid architecture presents a viable intermediate architecture for migrating from an OXC-based network to an OBS-based network. In addit we use queueing analysis to derive a formula which allows us to calculate the minimum number of wavelengths required to achieve a given blocking probability in this hybrid architecture. Simulation shows that this formula gives very accurate prediction. Future works include the study of the proposed architectures under different burst arrival processes.

REFERENCES


m wavelengths are used to carry bursts to edge OBS Y

Router 1

Router r

Carries bursts to all other edge OBS

Fig. 3. The general problem.

burst 1 ready for conversion
burst 2 ready for conversion
Queueing delay for burst 2

Fig. 4. A diagram illustrating the arrival of optical bursts at the electronic-to-optical interface. Burst 1 arrives when the conversion unit is idle and no delay is experienced by this burst. Burst 2 arrives when the conversion unit is busy, the conversion of burst 2 begins once the unit has finished converting burst 1.

Conversion unit is idle when burst 1 arrives. Conversion to optical burst begins immediately.

Fig. 5. This figure shows that \( z_t \leq m - 1 \) does not imply \((m - 1)\) or less sources are sending, where \( m \) is the number of wavelengths. There are three sources and \( 2 = m \) wavelengths. At time \( t \), \( z_t = 1 \leq m - 1 \) but 2 sources are sending.

This burst will be dropped
To two wavelengths

Fig. 6. This figure shows how blocking probability varies with the number of wavelengths. The upper bound is given by formula (6). The parameters are \( \frac{\lambda}{\mu} = 0.3 \), \( r = 32 \) and \( p = 0.31 \).

Fig. 7. This figure shows how blocking probability varies with the number of wavelengths. The upper bound is given by formula (6). The parameters are \( \frac{\lambda}{\mu} = 0.3 \), \( r = 32 \) and \( p = 0.9 \).

Fig. 8. This figure shows the number of wavelengths required to achieve a given blocking probability. The number of wavelengths required is predicted using the upper bound formula (6). The parameters are \( r = 32 \) and \( p = 1 \).