Performance Modeling of an Edge Optical Burst Switching Node

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Abstract

We consider an edge optical burst switching (OBS) node with or without converters. The OBS node serves a number of users, each connected to the switch over a fiber link that supports multiple wavelengths. Each wavelength is associated with a 3-state Markovian burst arrival process. The arrival process permits short and long bursts to be modeled. We model the edge OBS node as a closed non-product-form queueing network, and we develop a suite of approximate algorithms to analyze it. Our approximate algorithms have a good accuracy, and they provide insight into the effect of various system parameters on the performance of the edge OBS node.

1 Introduction

Optical burst switching (OBS) [5, 7] is a dWDM-based technology positioned between wavelength routing (i.e., circuit switching) and optical packet switching. The unit of transmission is a burst whose length in time is arbitrary. The transmission of each burst is preceded by the transmission of a control packet on a separate signaling channel. A source node starts transmitting a data burst after a delay (referred to as *offset*), following the transmission of the control packet.

`JumpStart` [1, 2] is an ARDA-supported research project between NCSU and MCNC that is investigating issues associated with *control protocols* for OBS networks. The signaling protocol follows the just-in-time (JIT) approach, and is based on the work by Wei and McFarland [6]. The `JumpStart` project represents an important first step in bringing OBS networks beyond the "paper concept" stage and into reality. The scope of project includes the development of a specification for a JIT signaling protocol, an implementation of the specifications in hardware and software, and an evaluation of the implementation in a testbed network environment. The defined protocol supports point-to-point and multicast communications, and the control message format is optimized to permit protocol implementation in hardware.

In this paper, we develop for the first time a queueing network model of an edge OBS node with burst arrival processes described by a general Markov process. Below, we describe briefly the operation of an edge OBS node in Section 2. In Section 3, we present the burst arrival process used in the queueing network model described in this paper. In Section 4, we describe a queueing network model of the edge OBS node. Section 5 describes a method for analyzing this queueing network. We validate the accuracy of the approximation algorithm in Section 6 by comparing it to simulation results, and we conclude the paper in Section 7.

2 The Edge OBS Node

We consider an OBS network consisting of OBS nodes (switches) interconnected by bidirectional fiber links. Each fiber link between a user and an OBS edge node, or between two adjacent OBS nodes, can support $W+1$ wavelengths. Of these, one wavelength (referred to as *control wavelength*) is used to transmit control packets, and the other W wavelengths (referred to as *burst wavelengths*) are used to transmit data bursts. A user is equipped with $W+1$ pairs of optical transceivers, each fixed tuned to one of the $W+1$ wavelengths.

Following the `JumpStart` JIT signaling protocol [2], a user first sends a `setup` message to its edge OBS node. The `setup` message includes the source and destination addresses, the wavelength on which the source prefers to transmit the burst, and other information. We assume that an OBS node consists of a non-blocking space-division switch fabric, with no optical buffers. If the edge node can switch the burst on the specified wavelength, it returns a `setup ack` message to the user. The `setup ack` message contains the offset field that informs the user how long it should wait before transmitting its burst. It is possible, however, that a `setup` message be refused if the preferred wave-

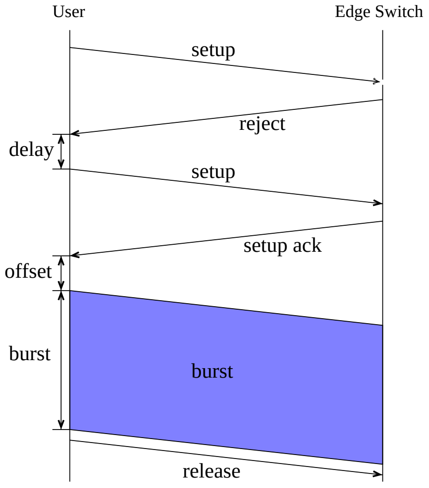

Figure 1: Signaling messages in `JumpStart`

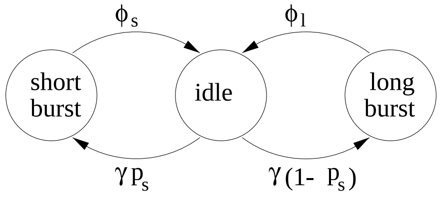

Figure 2: The burst arrival process

length on the destination output port is busy, or in the case of full wavelength converters, if all the wavelengths on the destination output port are busy. In this case, the edge node returns a `reject` message. The user goes through a random delay, and it then re-transmits the `setup` message. In our model, we assume that the user continues to re-transmit the `setup` message until it receives a `setup ack` message, although this assumption can be easily removed.

3 The Burst Arrival Process

Each burst wavelength from a user to an OBS edge switch is associated with a burst arrival process. We use the three-state Markov process shown in Figure 2 to model arrivals on a given burst wavelength. The arrival process may be in one of three states: `short burst`, `long burst`, or `idle`. If it is in the `short burst` (respectively, `long burst`) state, then the user is in the process of transmitting a short (respectively, long) burst on this wavelength. If it is in the `idle` state, then the user is not transmitting any burst on this wavelength. The duration of a burst, whether short or long, is assumed to be exponentially distributed.

The burst arrival process of Figure 2 is characterized completely by the following parameters: $1/\gamma$, the mean duration of the `idle` state; $1/\phi_s$ and $1/\phi_l$, the mean durations of the `short burst` and `long burst` states, respectively; p_s, the probability that a burst is a small burst, and p_i, the probability that a burst from the user has output port $i, i = 1, \cdots, P$, as its destination.

We use the squared coefficient of variation of the inter-arrival time of successive bursts (short or long), $c^2(A)$, as a measure of the burstiness of the arrival process. Unlike the Poisson process which is smooth ($c^2(A) = 1$), one may introduce any degree of burstiness into the arrival process by appropriately selecting the parameters of the three-state Markov process. For more details, the interested reader is referred to [8].

4 A Queueing Network Model of an Edge OBS Node

An edge OBS node is connected to a number of users and to a number of other OBS nodes. Consequently, it receives bursts both from users and other OBS nodes. In this work, we assume that there is no burst traffic from other OBS nodes to the edge OBS node, and we only consider the burst traffic from the users to the edge node. Let P and N denote the number of input (or output) ports of an edge node and the number of the users connected to the edge node, respectively. Note that, $P \geq N$.

4.1 Edge OBS Node Without Converters

Let us first consider an edge OBS node with no converters. In this case, a burst on an incoming wavelength can only be switched to the *same* wavelength on each output port, and user bursts arriving to the edge switch on different wavelengths do not interfere with each other. Consequently, the edge node can be decomposed into W sub-systems, one per burst wavelength, and this decomposition is exact. Each subsystem $w, w = 1, \cdots, W$, is a $P \times P$ switch with N users, but each input and output port has a single wavelength, which corresponds to wavelength w of the original edge switch. Therefore, each sub-system has N burst arrival processes.

The queueing network model of a sub-system is shown in Figure 3; it consists of $P + 1$ nodes numbered $0, 1, \cdots, P$. Node 0 is an infinite server node, and it represents the burst arrival processes which are in the `idle` state. Node $i, i = 1, \cdots, P$, represents the (single) wavelength on output port i. Each node i consists of a single *transmission server* and an *infinite server*. The customer (if any) occupying the transmis-

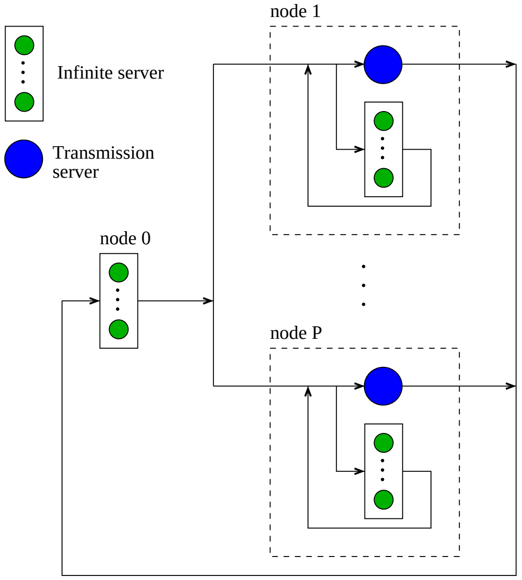

Figure 3: Queueing network model of a sub-system of an edge switch without converters

sion server represents the burst arrival process whose burst is being transmitted by output port i. The customers (if any) in the infinite server represent those burst arrival processes which are undergoing a delay before their users re-transmit the corresponding `setup` messages. The customers in the infinite server are often referred to in the literature as *orbiting* customers. The total number of customers in this closed queueing network model of a sub-system is equal to N (i.e., it is equal to the total number of burst arrival processes in the sub-system).

4.2 Edge OBS Node With Converters

Let us now consider an edge OBS switch with converters. In this case, a `setup` message for output port i of the switch is accepted as long as at least one wavelength is free on this output port. Otherwise, the `setup` message is rejected, and the user undergoes a delay before retransmitting the message. Clearly, the above decomposition of an edge switch into sub-systems per wavelength is no longer possible, since user bursts arriving on different wavelengths may interfere with each other. However, the edge switch *as a whole* can be modeled by a closed queueing network very similar to the one shown in Figure 3. The new queueing network consists of $P + 1$ nodes and a total of NW customers (since there are now NW arrival processes). Node 0 in the new queueing network is identical to node 0 in the network of Figure 3. Similarly, each node $i, i = 1, \cdots, P$, in the new queueing network corresponds to each of the output ports of the edge switch. The main difference is that each node $i, i = 1, \cdots, P$, consists of an infinite server and W (rather than one) transmission servers, each corresponding to one of the W wavelengths of output port i.

5 Analysis of the Queueing Network

The queueing network shown in Figure 3 is a non-product-form queueing network with Coxian service times. It consists of a single class of customers if all customers are associated with the same arrival process. Otherwise, it becomes a multi-class queueing network. The single class queueing network with or without converters was analyzed using Marie's algorithm [3]. To this end, we need to construct a *flow equivalent server* for each node $i, i = 1, \cdots, P$. Node 0 is an infinite server (i.e., a BCMP node), so we do not need to construct a flow equivalent node for it. We note that, to the best of our knowledge, Marie's method has not been applied to nodes with orbiting customers. Consequently, the derivation of a flow equivalent server for such a node is a new contribution. For an edge OBS switch without converters, we obtained the closed-form expression of the conditional throughput of the special node with orbiting customers. In the case of converters, we cannot obtain a closed-form solution, and we solve each node i numerically using the Gauss-Seidel method [4]. The multi-class queueing network was analyzed by decomposing it into a set of two-class networks. For more details, the interested reader is referred to [8].

6 Numerical Results

In this section, we present results to illustrate how the different system parameters affect the performance of the edge OBS node. In order to investigate the accuracy of our approximation algorithms, we also compare the approximate results to results obtained from a simulation program of an edge OBS switch.

We show results for $P = 16$ (i.e., a 16×16 edge switch) with $W = 32$ wavelengths per fiber and a hotspot traffic pattern such that 10% of all arriving traffic has output port 16 as its destination, while the remaining traffic is uniformly distributed among the other 15 output ports (i.e., $p_{16} = 0.1$, and $p_i = 0.06 \; \forall \; i \neq 16$). We assume that all customers are associated with the same arrival process. That is, our queueing network is a single class queueing network. We consider the following three performance measures: *switch throughput,* which is the sum over all output ports of the port throughput; *switch utilization*, i.e., the average across all output ports of the port utilization; and *mean waiting time of a user*, that is, the average waiting time until a user transmits a burst to the switch.

Figures 4-6 plot the three performance measures, respectively, against the number N of users attached to the edge switch; these figures show results for an OBS switch *without* converters. Two sets of plots are presented, each set corresponding to a different burst arrival process. For both arrival processes, the mean burst size has been set to 1, and the mean burst interarrival time has been set to 1.2. However, the squared coefficient of variation $c^2(A)$ of the burst interarrival times is set to 1 for one process, and to 100 for the other. The burst arrival process with $c^2(A) = 1$ is very smooth, while the one with $c^2(A) = 100$ is extremely bursty. Each set consists of two plots, one corresponding to simulation results and one corresponding to results obtained using the approximate analytical model we developed in Section 5.

From the three figures, we observe that there is a good agreement between the analytical and simulation results. We also observe that as the number of users increases, the switch throughput, switch utilization, and mean user waiting time all increase. We also see the dramatic effect that the burstiness of the arrival process can have on the performance of the edge OBS node. Specifically, for the smooth arrival process ($c^2(A) = 1$), the switch throughput and utilization increase with the number of users, while the mean waiting time remains low. When the arrival process is extremely bursty ($c^2(A) = 100$), on the other hand, increasing the traffic load by increasing the number of users has minimal effect on switch throughput or utilization, which remain at low levels, while it severely affects the mean waiting time.

Figures 7-9 are similar to Figures 4-6, respectively, but present results for an edge OBS node *with* converters. We consider two arrival processes as before, with the same parameters. We note again that there is a good agreement between the analytical and simulation results. We also observe two important differences compared to the results for a switch with no converters. First, for the same traffic load (i.e., number N of users), all performance measures are significantly improved. The second important observation is that, for all three measures considered here, there is little difference in the performance when the squared coefficient of variation (i.e., the burstiness) of the arrival process increases from 1 to 100 (compare to the switch with no converters where burstiness severely affects performance). Overall, the results indicate that, in addition to their well-known benefits, wavelength converters may also mitigate the adverse effects of even

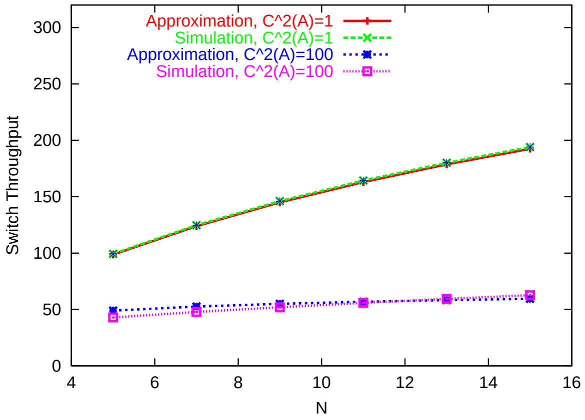

Figure 4: Switch throughput, no converters

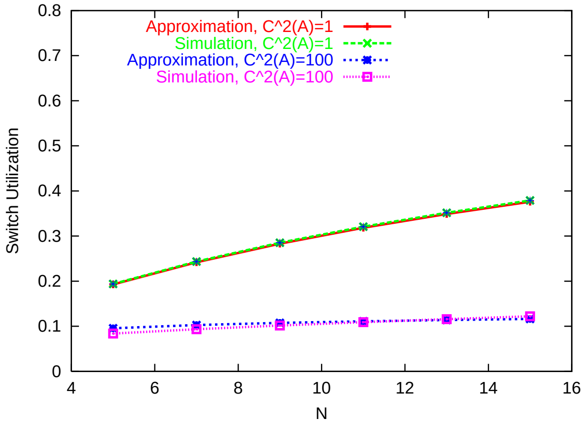

Figure 5: Switch utilization, no converters

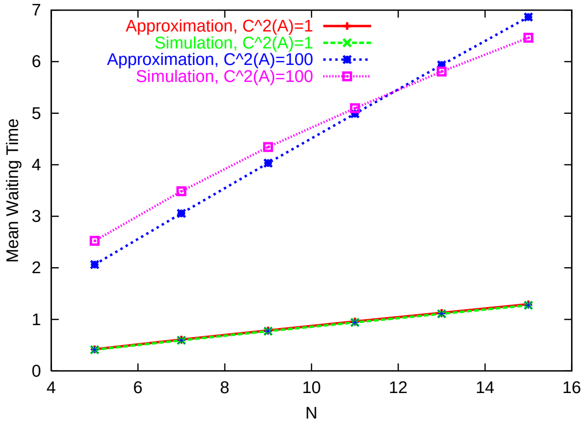

Figure 6: Mean waiting time, no converters

extremely bursty traffic on switch performance. This observation is quite important given the fact that, by definition, OBS networks will have to deal with bursty traffic.

7 Concluding Remarks

We have presented a new queueing network model of an edge OBS node. The model is quite general, and it permits us to study the performance of an edge switch under a wide range of traffic and operational scenarios, including: an arrival process with any desired degree of burstiness, and output ports with or without converters. We have developed approximate algorithms for each variant of the model, and we have presented numerical results which demonstrate the accuracy of our approximations. We are currently working on extensions of the queueing network models presented here to analyze a network of OBS nodes, including edge and core switches.

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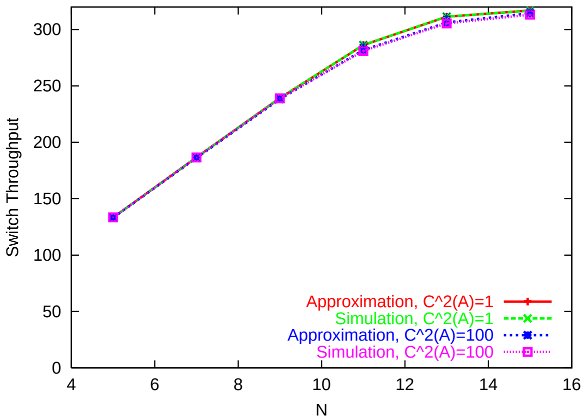

Figure 7: Switch throughput, with converters

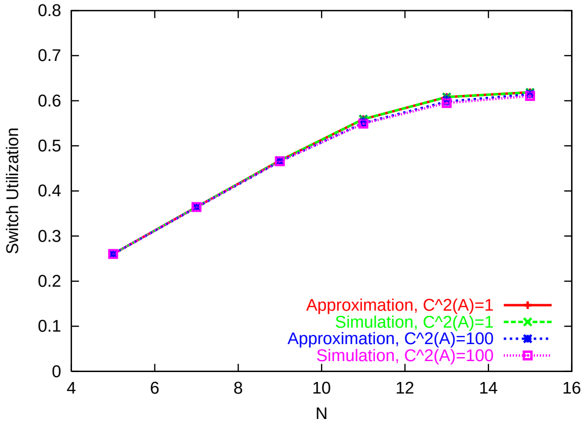

Figure 8: Switch utilization, with converters

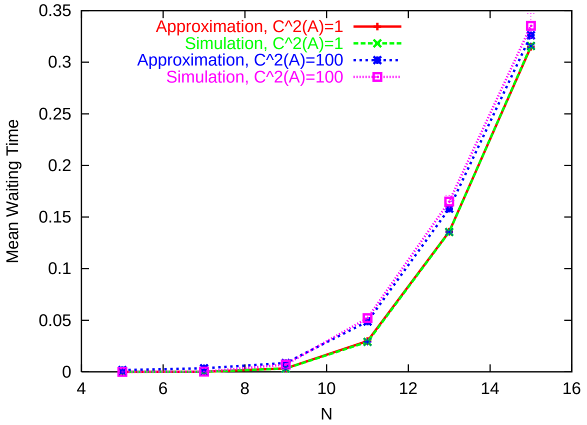

Figure 9: Mean waiting time, with converters