Performance Evaluation of an Optical Hybrid Switching System

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Abstract—**We propose a new optical hybrid switching system that takes advantage of both Optical Burst Switching (OBS) and Optical Circuit Switching (OCS) technologies. This system classifies incoming IP traffic flows into short-lived and long-lived flows. We model the system as a single server queue in a Markovian environment. The burst generation process is assumed to follow a two-state Markov Modulated Poisson Process (MMPP), and the service rate fluctuates based on the number of concurrent OCS sessions. Results for the mean delay and queue size are derived.**

I. Introduction

Optical network technologies are evolving rapidly in terms of multiplexing bandwidth and control capability. Research into optical networking is moving from circuit oriented networks to networks capable of packet switching.

It is known that the Optical Circuit Switching (OCS) networks achieve low bandwidth utilization with bursty traffic. Emerging Optical Burst Switching (OBS) technology aims to improve utilization of resources and transport data more efficiently than OCS [2]-[5]. OBS is an alternative switching technology that addresses the difficulty of buffering in optical devices. Whilst OCS is useful in carrying highly aggregated long-lived streams that require definite Quality of Service (QoS) guarantees, OBS has a role in efficiently carrying bursty best-effort traffic. Therefore it makes sense to consider a system which combines OCS and OBS. This combined circuit and burst switching system is the so-called hybrid switching system [7].

In this paper, we consider a combined OCS and OBS system and propose an analytical performance model of an OCS/OBS switch. We consider an IP-centric optical control network discussed in [8] and propose a new optical hybrid switching system using a flow classification technique. This technique classifies incoming IP traffic flows into short-lived and long-lived flows for QoS provisioning according to traffic characteristics in an optical hybrid switching environment. Short-lived flows are composed of a few packets and long-lived traffic typically indicate delay-sensitive real-time streams that are better suited for circuit (or wavelength) switching. The aim is to maximize network utilization while satisfying users' QoS requirements.

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For performance analysis, we consider a single bottleneck and assume that all awaiting bursts related to that bottleneck, in all remote sources (or buffers in Edge routers) are in a single combined server queue (SSQ).

The bandwidth available to OBS bursts in this SSQ is dependent upon the number of OCS sessions active on the hybrid switching system. The aim is to derive the mean queueing delay for the OBS traffic.

To capture the bursty nature of OBS data traffic, we model the arrival process as a two state Markov Modulated Poisson Process (MMPP). This is an alternating Markovian process with two arrival state. In [9] it is shown that MMPP can be used to model bursty traffic.

The SSQ is modeled as a queue in a Markovian environment [9,10] to reflect the stochastic nature of the capacity available to the OBS bursts given the effect of OCS connection loading. We use matrix analytic methods of [11] to obtain the numerical results of the delay of OBS bursts.

The remainder of the paper is organized as follows. In Section II, we propose a new optical hybrid switching system using flow classification technique in the optical edge router. Then, in Section III, the analytical model is described. In Section IV, the performance evaluation of hybrid switching system is presented. Finally in Section V, we give a numerical example of the technique.

II. Optical Hybrid Switching System

Today there is a consensus that IP routing and signaling protocols can be adapted for IP-centric control over optical network [12]. In particular, the MultiProtocol Lambda Switching (MPλS) control plane has been proposed for this purpose, which is essentially the MPLS control plane with optical extensions. More recently, generalized MPLS (GMPLS) has also been proposed to further extend support to multiple switching types. It provides a scalable and cost-effective approach that allows carriers and service providers to rapidly provision optical bandwidth to facilitate the deployment of new services. Thus we consider GMPLS-based optical switching network.

We propose a new implementation technique for flow classification in an optical edge router as shown in Figure 1. The optical edge router functional model for QoS provisioning is composed of a control module and a switching module. The control module has a control database such as the Label Information Base [13] and is connected to a GMPLS control module and also performs burst control and scheduling. The switching module combines aspects of circuit and burst switching. Incoming IP traffic flows are classified into short-lived and long-lived flows. The classification mechanism uses the existing adaptive flow classification presented in [14].

For short-lived traffic flows, we use OBS to achieve better bandwidth utilization because it allows statistical sharing of each wavelength among bursts. These flows are assembled into burst, with a separate burst for each class. For long-lived traffic flows such as video streaming, we aggregate these flows into aggregated flows for optical circuit/wavelength switching. We allocate capacity to the OCS traffic in preference to the OBS traffic. The bandwidth available to OBS bursts is the total bandwidth minus that consumed by the OCS traffic.

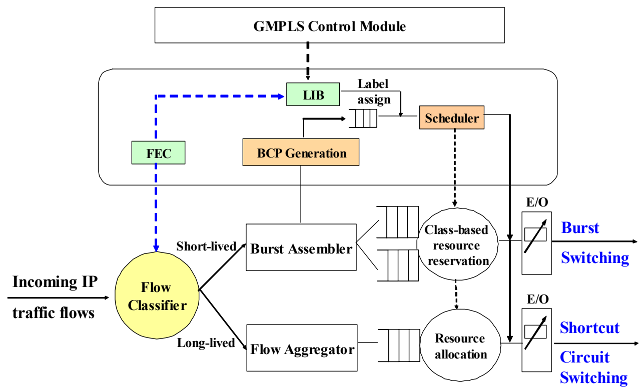


Fig. 1. Optical hybrid switching system functional model

III. Queueing Model

The queueing model is based on the assumption that the service capacity is made of an integer number of identical units. In principle, this could represent a bottlenecked link made of many wavelengths. The load on this bottlenecked link is made on OCS as well as OBS traffic. The entire service capacity remaining from the OCS usage is used to serve the entire OBS queued traffic in accordance with an SSQ model. The bursts in our SSQ are those competing for service in our bottlenecked link. Note that bursts in buffers which are not served by our bottlenecked link are not considered as part of the traffic here.

A. The short-lived traffic generation model for OBS

The generation process of OBS bursts is modeled using a two state MMPP. The MMPP process captures the bursty nature of short-lived traffic.

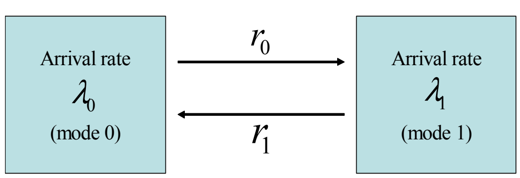


Fig. 2. Short-lived traffic model for OBS (MMPP)

As shown in Figure 2, a two state MMPP is an alternating Markovian process with two burst generation states, where the generation process in generation state m is a Poisson process with rate: λ_m, m = 0,1. The sojourn time in each generation state is exponentially distributed with the mean sojourn time in generation state 0 and 1 being r_0^{-1} and r_1^{-1} respectively. The values of the mean and the variance of MMPP traffic are given in [9]. Let N_t be the amount of work generated during time interval (0, t). For MMPP, the mean of N_t denoted $E[N_t]$, is:

$$E[N_t] = \frac{\lambda_0 r_1 + \lambda_1 r_0}{r_0 + r_1} \cdot t$$

and the variance of N_t, denoted V_t, is:

$$V_t = E[N_t]\left(1 + \frac{2(\lambda_0 - \lambda_1)^2 r_0 r_1}{(r_0 + r_1)^2(\lambda_0 r_1 + \lambda_1 r_0)} - \frac{2(\lambda_0 - \lambda_1)^2 r_0 r_1}{(r_0 + r_1)^3(\lambda_0 r_1 + \lambda_1 r_0)\cdot t}(1 - e^{-(r_0 + r_1)t})\right)$$

The queueing process of the OBS bursts can be represented as an SSQ process whereby the bandwidth available to OBS bursts in this SSQ is dependent upon the number of OCS sessions active on the hybrid switching system, and it fluctuates in accordance with OCS traffic loading. We are assuming here that the order of service of the various bursts at different location does not affect the average burst delay.

B. The long-lived traffic generation model for OCS

A long-lived traffic stream is allocated a channel for the duration of the connection. The long-lived traffic stream sends packets at a constant rate for duration of the connection. Admission of a long-lived traffic stream decreases the available capacity for the traffic stream and the completion of a long-lived traffic stream increases the capacity available for the traffic stream.

The admission and completion of the long-lived traffic stream OCS connections is modeled as an *M/M/k/k* process, where k is the maximum number of connections supported by the system. The long-lived traffic connection arrival process is Poisson with parameter λ_c and the connection holding time is assumed exponential with mean $1/\mu_c$.

IV. Queueing Analysis

We have modeled optical hybrid switching as a queue in a Markovian environment, and we follow Neuts' analysis of such a queueing model as described in [11] pages 254-264. The infinitesimal generator is first introduced here to describe the system, then, we review Neuts' solution as applied to our queueing problem.

A. Infinitesimal Generator

We will assume that the total link capacity C is divided into c units of capacity s, $s=C/c$, where s is the capacity used by a single long-lived OCS connection. Of the c units of capacity, d units are reserved exclusively for short-lived OBS bursts. Therefore only c-d capacity units are available for long-lived OCS connections as shown in Figure 3.

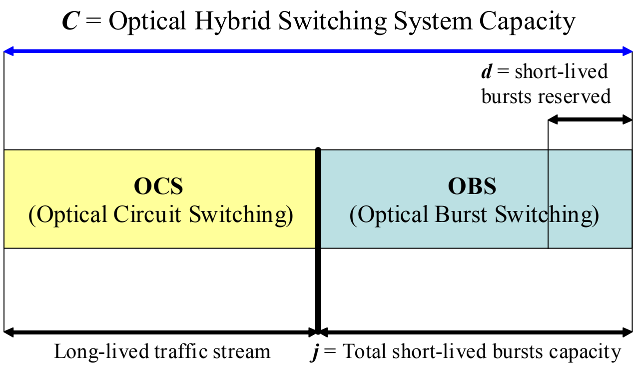
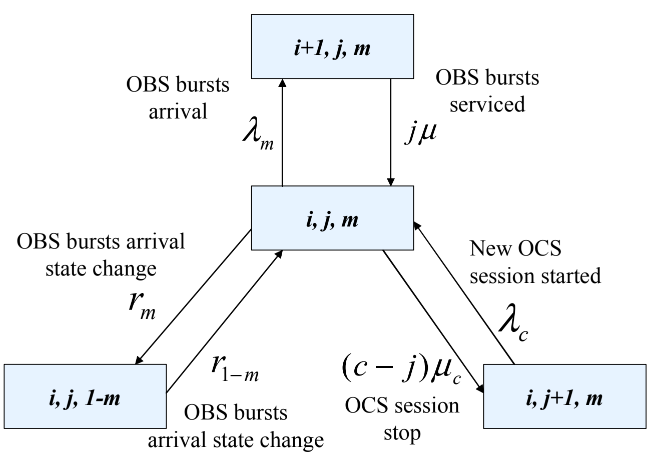


Fig. 3. Modeling optical hybrid switching system

The state of the system under consideration is denoted by the three dimensional vector (*i,j,m*) where *i* is the number of short-lived OBS bursts in the queue (including the one in service), *j* is the number of capacity units available for bursts, *m* is the arrival state (*m* takes the values 0 and 1). The OBS burst service rate is always equal to $j\mu$, where μ is the service rate provided by one capacity unit, and $j = d, d+1, d+2, \ldots, c$. The OBS burst arrival rate is λ_m, $m = 0,1$. All the possible state transitions are presented in Figure 4. Hence, Figure 4 defines the infinitesimal generator matrix *G*.



Where: $i = 0,1,2,\ldots$ $j = d,d+1,d+2,\ldots,c$ $m = 0,1$

Fig. 4. State transition diagram

The sum of the entries in each row of *G* is 0. Let $\hat{h}_{i,j,m}$ be the probability of being in state (*i,j,m*), the vector $\hat{h}$ is:

$$(\hat{h}_{0,d,0}, \hat{h}_{0,d,1}, \hat{h}_{0,d+1,0}, \hat{h}_{0,d+1,1}, \ldots, \hat{h}_{0,c,1}, \hat{h}_{1,d,0}, \hat{h}_{1,d,1}, \hat{h}_{1,d+1,0}, \hat{h}_{1,d+1,1}, \ldots, \hat{h}_{1,c,1}, \hat{h}_{2,d,0}, \hat{h}_{2,d,1}, \hat{h}_{2,d+1,0}, \hat{h}_{2,d+1,1}, \ldots)$$

The state transition balance equation is then

$$\hat{h}G = 0 .$$

The steady state queue size distribution x_i is related to $\hat{h}$ as such

$$x_i = \sum_m \sum_j \hat{h}_{i,j,m} .$$

We now obtain x_i by another approach, using Neuts' analysis.

B. Neuts' solution

The steady state queue size distribution vector x can be solved analytically by considering the OBS bursts SSQ's parameters being driven by a Markovian environment. The Markovian environment is comprised of two processes, the OCS connection arrivals and departures as well as the transition between OBS burst arrival state 0 and 1. These processes are independent, and determine the state of the environment *j* and *m*. The transition probability matrix of the Markovian environment is denoted *Q* and it is shown in Figure 5.

The Markovian random environment is the stochastic process that determines the number of OCS connections in the system and the OBS burst arrival state. As discussed, the OBS burst service rate fluctuates based on the OCS connections in the system. For each state of the environment, there is an appropriate OBS burst service rate in vector μ and OBS burst arrival rate in vector λ. The OBS burst service rates in each state of the environment (*j,m*) are:

$$\mu_{j,m} = \mu_j = j\mu, \quad m = 0,1 \text{ and } j = d, d+1, d+2, \ldots, c$$

Let vector μ be defined by

$$\mu = (d\mu, (d+1)\mu, (d+2)\mu, \ldots, c\mu)$$

The OBS bursts arrival rates in each state of the environment (*j,m*) are:

$$\lambda_{j,m} = \lambda_m, \quad m = 0,1 \text{ and } j = d, d+1, d+2, \ldots, c$$

Let vector λ be defined by

$$\lambda = (\lambda_0, \lambda_1, \lambda_0, \lambda_1, \lambda_0, \lambda_1, \ldots, \lambda_1)$$

For example, if $j = 50$ and $m = 1$ with $c = 120$ and $d = 10$, there are 120 capacity units with 10 reserved for OBS bursts only, and there are 70 OCS connections in the system as there are 50 capacity units available for OBS bursts. The OBS burst arrival state is 1. The OBS burst service process then has parameter 50μ (since 50 capacity units are allocated to serving OBS bursts) and OBS burst arrival process has parameter λ_1.

By a standard construction, the queue may be studied as a Quasi Birth-and-Death process with infinitesimal generator matrix *G*, given by

$$G = \begin{vmatrix} Q-\Delta(\lambda) & \Delta(\lambda) & 0 & 0 & \cdots \\ \Delta(\mu) & Q-\Delta(\lambda+\mu) & \Delta(\lambda) & 0 & \cdots \\ 0 & \Delta(\mu) & Q-\Delta(\lambda+\mu) & \Delta(\lambda) & \cdots \\ 0 & 0 & \Delta(\mu) & Q-\Delta(\lambda+\mu) & \cdots \\ \vdots & \vdots & \vdots & \vdots & \end{vmatrix}$$

where *Q* is the transition probability matrix of the Markovian environment as shown in Figure 5 and, $\Delta(z)$ the diagonal matrix of the vector *z*.

Assuming the queue is stable (mean arrival rate < mean service rate), to determine the queueing performance of the optical hybrid switching system, the stationary probability vector $x = (x_0, x_1, x_2, \ldots)$, which describes the probability distribution of the queue size, needs to be determined

$$Q=\begin{vmatrix} -r_0-(c-d)\mu & r_0 & (c-d)\mu_v & 0 & 0 & \cdots & 0 & 0 & 0 \\ r_1 & -r_1-(c-d)\mu_v & 0 & (c-d)\mu_v & 0 & \cdots & 0 & 0 & 0 \\ \lambda_v & 0 & -\lambda_v-r_0-(c-d-1)\mu_v & r_0 & (c-d-1)\mu_v & \cdots & 0 & 0 & 0 \\ 0 & \lambda_v & r_1 & -\lambda_v-r_1-(c-d-1)\mu_v & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & \lambda_v & 0 & -\lambda_v-r_0-(c-d-2)\mu_v & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & -\lambda_v-r_1-\mu_v & 0 & \mu_v \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & -\lambda_v-r_0 & r_0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & \lambda_v & r_1 & -\lambda_v-r_1 \end{vmatrix}$$

Fig. 5. The matrix Q

Using Neuts' formalization of the M/M/1 queue in a Markovian environment [11], this problem is translated into finding the minimal solution for the matrix R, which satisfies the matrix equation

$$R^2\Delta(\mu)+R(Q-\Delta(\lambda+\mu))+\Delta(\lambda)=0$$

where Q is the transition probability matrix of the Markovian environment, and $\Delta(z)$ the diagonal matrix of the vector z.

The matrix R can be evaluated using a cyclic reduction algorithm described in [10],[15]-[18]. The stationary probability vector x of the stable queue is given by:

$$x_k=\pi(I-R)R^k \quad for\ k\geq 0$$

where π is the stationary probability vector of Q (Eq. (6.2.5) from [11]). The vector π is given by solving $\pi\cdot Q=0$ by, for example, successive relaxation.

The mean queue size is computed using the stationary probability vector x. The mean OBS burst delay is found using Little's law. Burst delay is the time from the generation of the burst to the time the last bit of burst is sent. The mean delay is thus obtained as follows:

$$mean\ \ OBS\ \ burst\ \ arrival\ \ rate=\frac{\lambda_0 r_1+\lambda_1 r_0}{r_0+r_1}$$

$$mean\ \ queue\ \ size=\sum_{i=1}^{i=\infty}x_i\cdot i$$

$$mean\ \ OBS\ \ burst\ \ delay=\frac{mean\ \ queue\ \ size}{mean\ \ burst\ \ arrival\ \ rate}$$

$$utilizaton=\frac{mean\ arrival\ rate}{mean\ service\ rate}.$$

V. NUMERICAL RESULTS

The analysis was performed for an optical hybrid switching system of particular parameters. There are 120 available capacity units of link. Out of the 120 available, 10 capacity units are reserved exclusively for OBS bursts only. Each link is 10Gbps. The mean duration of an OCS session is 3 minutes. The OCS load is chosen so that the capacity available to the OCS connection has a utilization of 30%. Table 1 lists all of the parameters used. These parameters were used to obtain a result using analytical approach.

TABLE 1.
Model parameters

Parameter	Value	Meaning
λ_0	variable	OBS state 0 burst generation rate
λ_1	$\lambda_1=5\lambda_0$	OBS state 1 burst generation rate
r_0	0.00001	State 0 to 1 transition rate
r_1	0.000001	State 1 to 0 transition rate
μ	1/1000	Mean OBS burst service rate per unit of capacity
c	120	Total capacity units of link
d	10	Capacity units reserved for OBS bursts only
μ_c	1/180000	1/(OCS connection hold time)
λ_c	$0.3(c-d)\mu_c$	OCS connection establishment rate

In Figure 6 we present the result for the mean delay versus utilization for OBS bursts. The mean delay is rapidly increased for high utilization (over 0.7). Thus, this result indicates that in order to operate an optical hybrid system with reasonable burst delays the utilization must be kept below 70%. Similarly, the mean queue size is also increased for high utilization as shown in Figure 7. Figure 8 shows the queue size probability distribution for OBS bursts when utilization is 0.8.

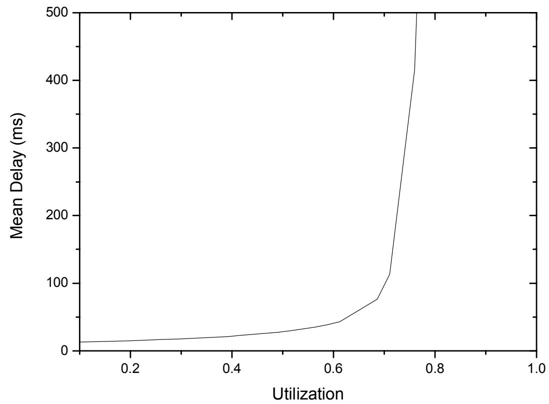


Fig. 6. Mean delay versus utilization for OBS bursts

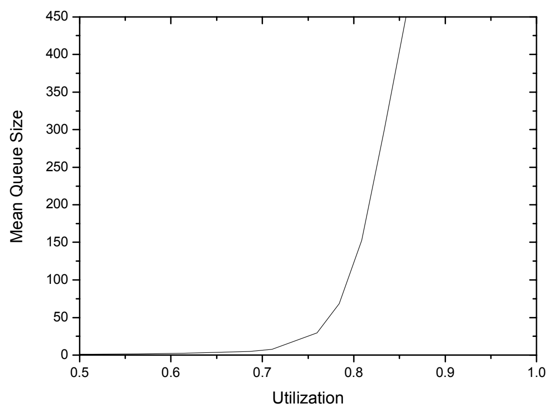


Fig. 7. Mean queue size versus utilization

VI. Conclusion

In this paper, we have proposed a new optical hybrid switching system which combines OBS and OCS. We also presented a simple analytical model of this system. We have used MMPP to model the bursty nature of OBS data traffic and matrix geometric techniques to obtain queueing performance results. This paper has provided an analytical tool for provisioning capacity in an optical hybrid system to increase network utilization subject to meeting QoS requirements.

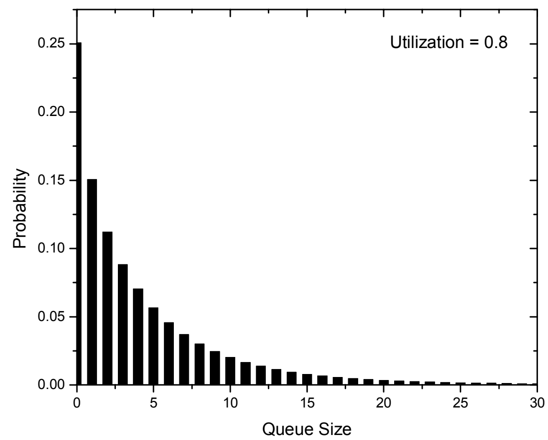


Fig. 8. Queue size probability for OBS bursts

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