On Optimal Ingress Treatment of Delay-Sensitive Traffic in Multi-Class OBS Systems

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***Abstract*— We examine the effect of optical switching speed and edge traffic-grooming strategies on the performance of premium-class traffic in multi-class OBS networks. While previous studies have examined optimal burst assembly and optimal offset provisioning, this is the first study to examine both simultaneously and the first study to include the effects of finite optical switching speed. We find that the minimum achievable premium-class blocking probability is limited by the optical switch reconfiguration time and the premium-class delay requirements. We present an analytical method for finding the optimal combination of burst-assembly timeouts and offset sizes at the ingress of the network that maximizes the premium-class performance. Via a numerical study, we examine the relationship between optical switching speed and the maximum achievable premium-class performance. We find that there exists a cutoff switching speed beyond which further speed-ups yield negligible throughput gains. We give a direct expression for this cutoff switching speed as a function of the premium-class delay constraint and desired low-class switching overhead. For a system in which the premium-class delay guarantee is 20 ms, this cutoff was found to occur at approximately $10\ \mu$s.**

I. INTRODUCTION

Optical Burst Switching (OBS) is a promising architecture for accommodating bursty traffic and providing sub-wavelength granularity in WDM networks. In OBS, packets are aggregated electronically at the ingress of the network into long bursts that are forwarded all-optically through the network. The header and payload of bursts are separated by a time offset to allow for the time required to electronically process the header (control packet) at intermediate nodes [1]. Because it employs electronic control-packet processing and assembles packets into long bursts, OBS does not require the complex optical processing or the ultra fast optical switching typically required for optical packet switching, yet still retains much of optical packet switching's flexibility and efficiency.

In this paper, we consider Just-Enough-Time (JET) OBS systems [2] with full wavelength conversion, no FDL buffers, and timer-based burst assembly. Timer-based burst assembly has been proposed as a practical burst-aggregation scheme for delay sensitive traffic, as it bounds the ingress delay experienced by incoming packets. At each ingress buffer, a timer is started when the first packet arrives. Packets accumulate in the buffer until the timer expires, at which point the entire buffer contents are transmitted as a single burst [3].

In JET OBS, resources are reserved in the switch for exactly the duration of the burst [4], so other bursts can be scheduled in the time period between control packets and their bursts. Multiple classes can be implemented in JET OBS by introducing an extended offset between high-class bursts and their control packets [4]. Increasing the size of this offset will generally increase the priority of premium-class bursts, thereby decreasing their blocking probability. Premium-class throughput can also be improved by increasing the duration of the premium-class burst-assembly timer, which increases the average burst length and, therefore, decreases the overhead due to switching guardbands. Thus, designers have two variables that they can select at the network ingress to increase premium-class throughput at the cost of increased premium-class delay.

A number of applications carried by premium-class bursts may have strict delay requirements that limit the maximum permissible ingress delay. Thus, OBS designers must decide what fraction of the ingress delay should be allocated to each of the burst-aggregation time and the offset time to maximize the premium-class throughput. Although there have been previous studies on optimal burst assembly in OBS [5], [6], none have considered the additional degree of freedom afforded by extended offsets or the effect of optical switch reconfiguration times.

In this paper, we examine multi-class OBS systems in which high-class performance requirements are specified in terms of blocking probability and delay. We describe methods for selecting the burst-assembly timeout and offset size to satisfy blocking and delay performance requirements, and we derive an analytical model that quantifies how the optical switching speed and premium-class delay constraint, together, determine the minimum achievable premium-class blocking probability. Using this result, we present an expression for the target optical switching speed of a given system as a function of the desired low-class overhead and the maximum allowable premium-class ingress delay.

II. ANALYTICAL MODEL

In this section we derive an analytical model to compute the premium-class blocking probability in multi-class OBS systems that use timer-based burst aggregation and that have non-zero switching times.

We assume that the input traffic follows a self-similar process with a Hurst parameter of H, a coefficient of variation of C_v, and an offered load of ρ. We also assume that a timer-based burst-assembly mechanism with a timeout (or threshold) value of θ is applied to incoming traffic. For blocking analysis purposes, the resulting post-assembly burst stream can be accurately modelled by a Poisson burst-arrival process with mean arrival rate ρ/θ and a Gaussian burst-length distribution with mean θ and variance $C_v\theta^2H$ [7].

To model the overhead due to the non-zero optical switch reconfiguration time, a switching guardband of constant length τ_{sw} is added to each burst. The resulting burst-length distribution will be Gaussian with a mean of $\theta + \tau_{sw}$, a variance of $C_v\theta^{2H}$, and a distribution function of

$$F_L(l) = \frac{1}{2}\left(1 - \operatorname{erf}\left[\frac{l - \theta - \tau_{sw}}{\sqrt{2C_v}\theta^H}\right]\right). \qquad (1)$$

The arrival time of each burst will be shifted by a constant value, so the arrival process will remain Poissonian with mean arrival rate ρ/θ.

In [8], we derived an expression for the blocking probability of the premium class in a multi-class OBS system with an arbitrary number of channels, arbitrary burst-length distributions and arbitrary offsets. Using this result and the distribution in (1), the premium-class blocking probability in a two-class OBS system using timer-based burst aggregation and non-zero switching time can be expressed as

$$Pb_h = 1 - \sum_{m=0}^{W-1} \frac{\eta_h^m e^{-\eta_h}}{m!} \qquad (2)$$

where

$$\begin{aligned}\eta_h = {} & \frac{\rho_h(\theta_h + \tau_{sw})}{\theta_h} \\ & + \frac{\rho_\ell}{\theta_\ell}\left\{\theta_\ell + \tau_{sw} - \frac{1}{2}\int_0^{\Omega_h} 1 - \operatorname{erf}\left(\frac{l - \theta_\ell - \tau_{sw}}{\sqrt{2C_{v\ell}\theta_\ell^{H_\ell}}}\right) dl\right\}.\end{aligned} \qquad (3)$$

and where W is the number of wavelengths in the system, θ_h and θ_ℓ are the low-class and high-class burst-assembly threshold values respectively, H_ℓ and $C_{v\ell}$ are the low-class Hurst parameter and coefficient of variation respectively, and Ω_h is the size of the premium-class offset time. Although we consider a two-class system here, the model can be extended to an arbitrary number of classes.

III. INGRESS PARAMETER SELECTION

For the two-class OBS system under consideration, three ingress parameters—the high-class and low-class burst-assembly timeouts and the high-class extended offset size—must be specified. Since the majority of traffic in the system is assumed to be best-effort, low-priority traffic, we can minimize the overall switching overhead in the system by selecting the low-class burst-assembly threshold to be much larger than the optical switching time. For this study, we therefore select $\theta_\ell = 200\tau_{sw}$ and focus on the optimal selection of the high-class ingress parameters.

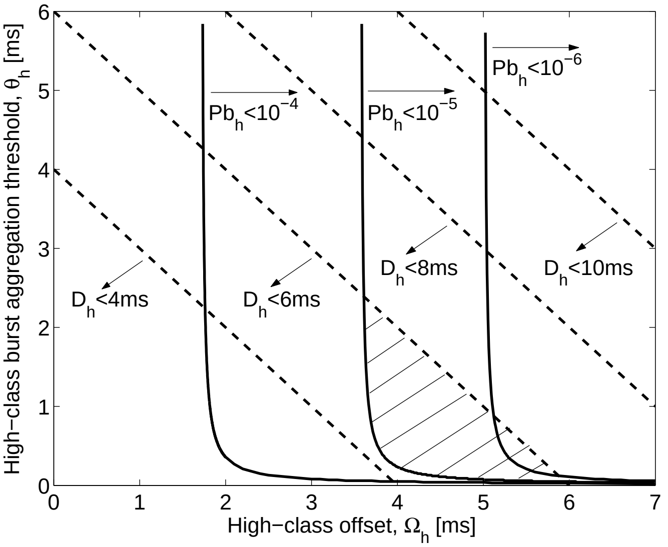

Fig. 1. The area to the right of each Pb_h curve contains operating points that satisfy a particular premium-class blocking probability requirement. The area to the left of each D_h curve contains operating points that satisfy a particular premium-class delay constraint. The intersection of two such regions defines a feasible operating region, as indicated by the shaded region for the case of $Pb_h < 10^{-5}$ and $D_h < 6\ ms$.

A. Feasibility Region of Ingress Parameters

Here we examine an OBS system with 16 wavelengths and an optical switching time of 50 μs. The offered loads of premium-class traffic and best-effort traffic were 1 and 5 respectively. The input traffic stream of both classes consisted of self-similar Fractional Gaussian Noise processes with Hurst parameter and coefficient of variation of 0.78 and 0.1 respectively (inferred from the Bellcore traces [9]).

We define the blocking probability and delay requirements of the premium-class traffic as Pb_h^{max} and D_h^{max} respectively. We define the *feasible operating region* as the set of burst-aggregation times and high-class offsets that simultaneously satisfy these QoS requirements.

Fig. 1 is a two-dimensional representation of all possible combinations of premium-class burst-assembly timeout and offset values. Any given delay or blocking probability requirement can be represented as a curve on this graph. The area to the right of each Pb_h corresponds to operating points that satisfy a particular premium-class blocking probability requirement. The area below each D_h curve correspond to operating points that satisfy a particular premium-class delay constraint. Thus, for a given pair of premium-class QoS constraints, the feasible operating region is represented as the area between two such curves. In general, the location and the size of this region will depend on all the OBS system's parameters, including the ingress traffic characteristics, the optical switching time, the desired low-class switching overhead, and the premium-class QoS constraints. For example,

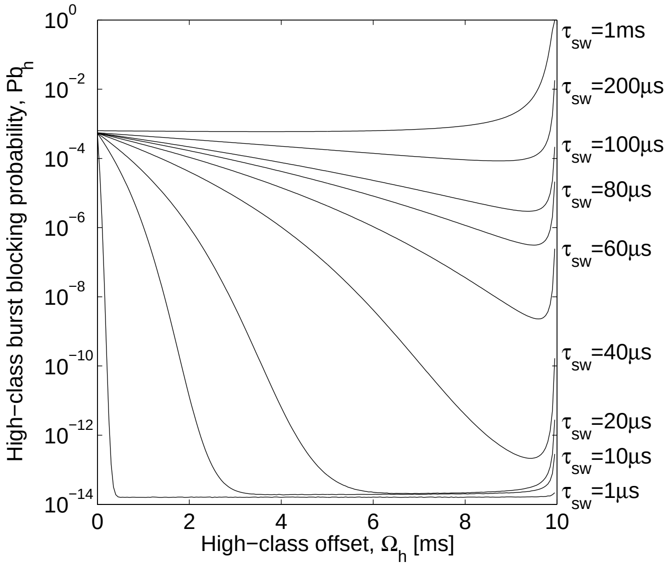

Fig. 2. Premium-class blocking probability versus premium-class offset size for a system in which the maximum allowable premium-class ingress delay D_h^{max} is 10 ms. Each curve corresponds to a different optical switch reconfiguration time τ_{sw}. For each value of τ_{sw}, the premium-class blocking can be minimized by optimally selecting the offset size Ω_h and the burst-assembly time θ_h (where $D_h^{max} = \theta_h + \Omega_h$).

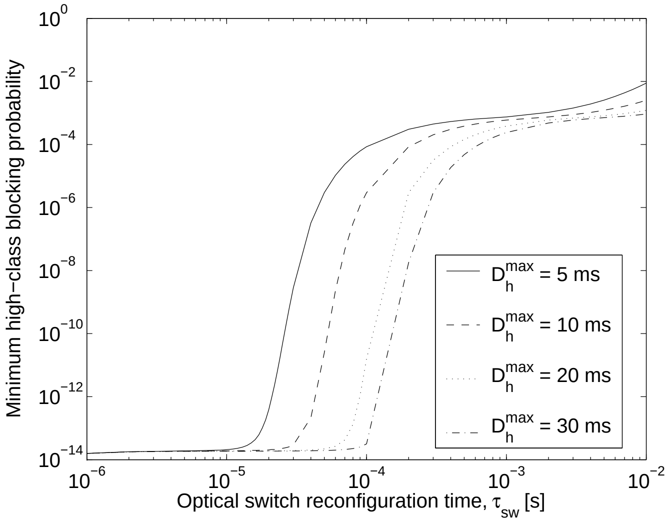

Fig. 3. Relationship between minimum achievable premium-class blocking probability and optical switch reconfiguration time. Each curve represents a different maximum allowable ingress delay D_h^{max}. Significant throughput gains may be realized by faster optical switching. However, for all systems, there is a cutoff switching reconfiguration time that achieves the minimum possible blocking probability. This cutoff represents a natural target switching speed for OBS switch designers.

the shaded region in Fig. 1 represents the feasible operating region for $D_h^{max} = 6$ ms and $Pb_h^{max} = 10^{-5}$. Alternatively, if the delay and blocking constraints are $D_{max} = 4$ ms and $Pb_h^{max} = 10^{-5}$ respectively, the feasible operating region is null, implying that no combination of Ω_h and θ_h can simultaneously satisfy both of these QoS requirements.

B. Effect of Switching Speed on Premium-Class Performance

Because of the premium-class delay constraint, there is an inherent tradeoff between the burst-assembly timeout and the premium-class offset size. Fig. 2 plots the premium-class blocking probability versus the premium-class offset size for the same system parameters as were used in Fig. 1. Each curve corresponds to a different switching speed, and the maximum allowable ingress delay for high-class traffic was 10 ms.

For each curve, the high-class priority increases as the size of the high-class offset is increased. At the same time, however, the burst-assembly threshold decreases, so the switching overhead increases. For small values of offset, the effect of the increased priority dominates, so the blocking probability decreases. As the offset size approaches the maximum allowable ingress delay, the burst-assembly threshold and corresponding burst lengths become very short, so the switching overhead dominates, and the blocking probability begins to increase.

C. Optimal Ingress Parameter Selection

From Fig. 2, it is evident that there exists an optimal pair of values for θ_h and Ω_h that minimizes the premium-class blocking probability for a given value of D_h^{max}. The task of finding these optimal values can be described as a constrained optimization problem in which we minimize the premium-class blocking probability given in (2) subject to the delay constraint $\theta_h + \Omega_h < D_h^{max}$.

By direct application of the method of Lagrange multipliers, we obtain the following pair of simultaneous equations

$$\frac{\partial Pb_h}{\partial \theta_h} = \frac{\partial Pb_h}{\partial \Omega_h} \tag{4}$$

$$\theta_h + \Omega_h = D_h^{max}. \tag{5}$$

Substituting (2) into (4), performing both differentiations, and combining the resulting equation with (5) yields

$$1 - \operatorname{erf}\left(\frac{D_h^{max} - \theta_h - \theta_\ell - \tau_{sw}}{\sqrt{2C_v}\theta_\ell^{H_\ell}}\right) = \frac{2\theta_\ell \tau_{sw}}{\theta_h^2}\frac{\rho_h}{\rho_\ell}. \tag{6}$$

Equation (6) can be solved numerically to obtain optimal values for θ_h and Ω_h that minimize the premium-class blocking probability while satisfying its maximum delay constraint.

Fig. 3 plots the minimum achievable high-class blocking probability versus the optical switch reconfiguration time for various values of D_h^{max} for an OBS system with the same parameters as those in Fig. 2. The graph implies that the maximal throughput of the premium class can be strongly affected by both the switching speed and the maximum delay constraint of the premium class. The shape of the curves implies that the premium-class blocking probability can be improved by multiple orders of magnitude by decreasing the switch reconfiguration time down to a threshold point. However, beyond this threshold, further increases in switching speed yield very minor gains. This cutoff point can be conservatively defined as:

$$\tau_{sw}^{cutoff} = 0.1 * D_h^{max} * O_\ell \tag{7}$$

where O_ℓ is the desired low-class switching-guardband overhead (0.5% in this example). For example, in Fig. 2, for the case of $D_h^{max} = 20$ ms, a switching time of approximately 10 μs is sufficient to achieve maximal throughput.

The expression in (7) is found to be valid for a wide range of D_h^{max}, O_ℓ, ρ_ℓ, ρ_h, and H_ℓ values. The relation in (7) is very useful, as it gives a target switching speed for efficient operation of a given OBS system. It also implies that τ_{sw}^{cutoff} is relatively insensitive to the number of wavelengths in the system or to the ingress traffic characteristics.

IV. CONCLUSIONS

We have shown that the maximum achievable throughput of premium-class traffic is determined by the combined effects of the premium-class delay requirements and the optical switch reconfiguration time. We presented an analytical method for finding the premium-class offset size and bursts-assembly timeout that maximized premium-class throughput while satisfying premium-class delay guarantees. We quantified the effect of switching speed on the maximum achievable throughput of premium-class traffic, and we presented a formula that determines the minimum switching speed required to achieve maximal throughput. For a system in which the premium-class delay guarantee is 20 ms, a switching time of 10 μs was sufficient to achieves optimal performance.

REFERENCES

[1] C. Qiao, "Labeled optical burst switching for IP-over-WDM integration," *IEEE Commun. Mag.*, vol. 38, pp. 104–114, Sep. 2000.

[2] M. Yoo and C. Qiao, "Just-enough-time (JET): a high speed protocol for bursty traffic in optical networks," in *Proc. IEEE/LEOS Summer Topical Meetings*, pp. 26–27, 1997.

[3] A. Ge, F. Callegati, and L. Tamil, "On optical burst switching and self-similar traffic," *IEEE Commun. Lett.*, vol. 4, pp. 98–100, Mar. 2000.

[4] M. Yoo, C. Qiao, and S. Dixit, "Optical burst switching for service differentiation in the next-generation optical Internet," *IEEE Commun. Mag.*, vol. 39, pp. 98–104, Feb. 2001.

[5] J. White, M. Zukerman, and H. L. Vu, "A framework for optical burst switching network design," *IEEE Commun. Lett.*, vol. 6, pp. 268–270, Jun. 2002.

[6] V. Vokkarane, K. Haridoss, and J. Jue, "Threshold-based burst assembly policies for QoS support in optical burst-switched networks," in *Proc. Opticomm '02*, pp. 125–136, 2002.

[7] M. Izal and J. Aracil, "On the influence of self-similarity on optical burst switching traffic," in *Proc. Globecom '02*, pp. 2308–2312, 2002.

[8] N. Barakat and E. H. Sargent, "Quantifying the effect of extended offsets in optical burst switching networks," in *Proc. CCECE '04*, pp. 2331–2335, May. 2004.

[9] I. Norris, "On the use of fractional brownian motion in the theory of connectionless networks," *IEEE J. Select. Areas Commun.*, vol. 13, pp. 953–962, Aug. 1995.