

Performance Enhancement of Optical Burst Switching using Burst Segmentation

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Abstract—In this paper we provide an analytical framework for studying the performance of Optical Burst Switching (OBS) networks using Burst Segmentation. We first consider a single link model to evaluate the blocking probability of OBS using Burst Segmentation and confirm it by simulation. We use this analysis to demonstrate the benefit of Burst Segmentation over the well-known Just-Enough-Time (JET) policy for the single link case. We then extend these models to a network scenario using a reduced load fixed point approximation to evaluate blocking probabilities and to show the advantages provided by Burst Segmentation for OBS networks.

I. INTRODUCTION

Optical Burst Switching (OBS) (see [1], [2], [3], [4], and [5]) has been proposed as an efficient switching technique to exploit the terabit bandwidth of Wavelength Division Multiplexing (WDM) transmission technology. In OBS, IP packets with a common destination arriving at the same ingress node are aggregated into large bursts, switched and routed as one unit. Since only one header is associated with each burst, the header processing is amortized over more data, and the switch fabric can be reconfigured on a longer timescale. The header (or control packet) precedes the burst payload and attempts to reserve switching and transmission resources at each switch and output port along the route.

A key feature in OBS is that the header precedes the payload by an offset time and is usually transmitted on a dedicated signalling wavelength. The payload follows the header without waiting for acknowledgment. At every switch, if the requested resources are available, the burst is transparently switched to its next hop; otherwise, the burst is blocked and some fraction (possibly all) of the data is lost. OBS sits somewhere between circuit switching and packet switching: the path is not acknowledged end-to-end, leading to resource usage that is ultimately wasted when a burst is blocked; and the current

limited ability for buffering in the optical domain means that burst data cuts through the switch and uses route links in a time-synchronous manner, whereas packets use them asynchronously due to buffering.

Note that while optical micro-electro-mechanical switches (MEMS) can only provide fabric reconfiguration time in the order of a few milliseconds, switches based on Semiconductor Optical Amplifiers (SOAs) achieve reconfiguration time in the order of a few nanoseconds. More recent techniques [11] even achieve reconfiguration time in the order of a few hundred picoseconds. Moreover, Electro-Absorption Modulator based devices capable of reconfiguration time in the order of a few picoseconds [12], [14], are already being used in research laboratories. With support from these technologies, OBS is likely to become a feasible switching technique in the near future.

To this end it is important to maximise usage of the optical bandwidth under OBS and to be able to understand and model the reservation protocols involved. Several OBS reservation protocols have been proposed by researchers. In this paper we consider the merits of two major schemes, the Just-Enough Time (JET) protocol and the Burst Segmentation protocol and we provide analytical results which demonstrate the improved performance offered by the Burst Segmentation policy. Under JET [1] the control packet contains the burst length and requests link bandwidth from the predetermined time offset and for the duration of the burst transmission. In Burst Segmentation [3] and [4] on the other hand, the control packet contains the burst length and reserves capacity from the first instant when a wavelength becomes available. The initial portion of the burst which is not served before a wavelength becomes free is discarded and lost, i.e. the burst is segmented. The remainder is transmitted successfully as a truncated burst.

In Section II we provide single node, single link analyses of JET and Burst Segmentation. Whilst these techniques provide crude upper bounds on link blocking probability they cannot capture network effects due to blocking along the network routes, and hence in Section III we use the analysis framework for OBS networks presented in [13] to make a comparison of JET and Burst Segmentation in a network scenario. Finally, the conclusions are presented in Section IV.

II. SINGLE NODE ANALYSIS

A. JET policy

Since OBS is a bufferless system, the $M/M/k/k$ queueing model is a standard analysis approach [1], [2]. This model assumes that the burst arrival process at a given output port of the an optical burst switch is a Poisson process with rate λ . If the burst duration is exponentially distributed with mean $1/\mu$ and the number of wavelengths on the output fibre is k then the Erlang B formula gives the probability of burst blocking:

$$P_B(k, A) = \frac{A^k/k!}{\sum_{m=0}^k A^m/m!}, \quad (1)$$

where $A = \frac{\lambda}{\mu}$ is the offered traffic load. Due to the insensitivity of the Erlang B formula to the service time distribution, the burst duration distribution can be relaxed to be a general distribution. This model is suitable for the JET and JIT reservation policies in which a burst is either accepted or rejected in its entirety. In this case, the packet loss probability is the same as the burst loss probability [3].

B. Burst Segmentation policy

The Burst Segmentation policy cannot be modelled by (1) since blocked bursts are segmented and maybe partially rejected under this regime [3]. However, this system can be modelled simply using the $M/G/\infty$ queueing model. In this model, the first k servers of the $M/G/\infty$ system are real servers representing actual wavelength channels. The remaining servers are pseudo-servers which are used simply to record the arrival of a burst to the full system. When a burst is "served" by a pseudo server, its payload is being lost and the burst itself is segmented. If the system is full and there are occupied pseudo-servers, when one of the real servers becomes free, the remainder of the first blocked burst is moved to the free real server so that its truncated portion is given service and is not lost. In this way the $M/G/\infty$ system is able to model the segmentation of bursts which are blocked, throwing away the blocked portion and retaining the useable part.

In the $M/G/\infty$ model, if k or less servers are busy then all bursts in the system are being successfully transmitted on a wavelength channel and no loss is occurring. In the case of $k+j$ bursts in the system, $j \geq 1$, then j of the bursts are losing packets, waiting for one of the k wavelengths to become free. Thus j out of every $k+j$ packets are lost in this case. The packet loss probability is

$$P_{BS}(k, A) = \frac{E[L]}{A}. \quad (2)$$

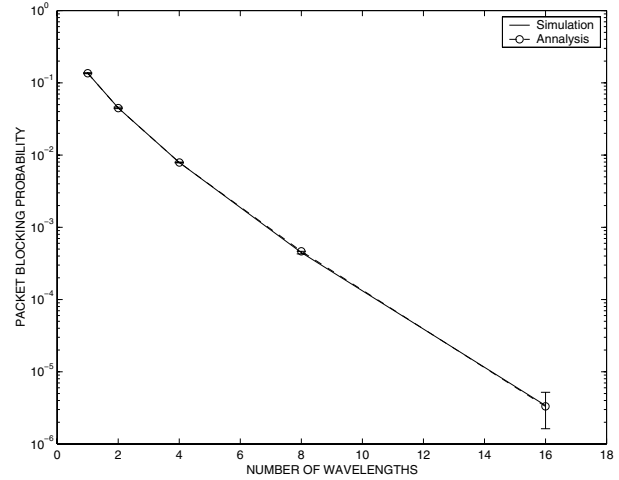


Fig. 1. Comparison between analytical and simulation results; Blocking probability versus number of wavelength.

In this equation $E[L]$ is the mean loss rate given by

$$E[L] = \sum_{j=1}^{\infty} j \cdot P(k+j), \quad (3)$$

where $P(k+j)$ is the probability that $(k+j)$ servers are busy in an $M/G/\infty$ model, which is well known [10] to be

$$P(k+j) = A^{k+j} \frac{e^{-A}}{(k+j)!}, \quad j = 1, 2, \dots \quad (4)$$

Thus we have a simple formulation for the packet loss probability in Burst Segmentation for a Poisson arrival process. It is interesting to note that Detti et. al. [3] have analysed Burst Segmentation by supposing that a number of ON/OFF sources contribute to the input process at a switch output, which models the fact that the input traffic comes from individual wavelengths on a number of switch input ports. This analysis arrives at the Engset formula, with the exact value of traffic lost depending on the number of contributing sources. Since the superposition of a large number of ON/OFF sources tends to a Poisson process in the limit, we can regard the $M/G/\infty$ model as a simplified limiting case of many sources which can provide a more convenient basis for network modelling, as in Section III.

C. Confirmation by Simulation

In Fig. 1, the simulation and analytical results for the packet blocking probability using Burst Segmentation for a single link have been plotted as a function of the number of available wavelength for a case where the traffic load per wavelength is 0.3. For different traffic loads, we depict the simulation and analytical results using 8 wavelengths in Fig. 2.

The results show that the analytical model is in very good agreement with the simulation results. The simulation results are presented with their respective 95 % confidence intervals based on the Student's t-distribution. (Note that the 95 % confidence intervals are so small that at times, it is hard to see them on the figures.)

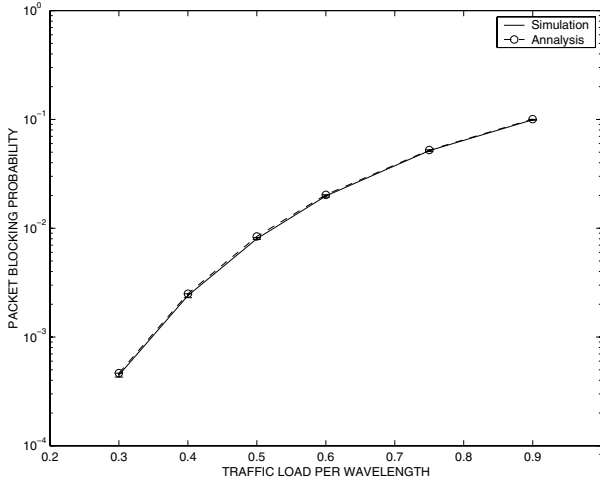


Fig. 2. Comparison between analytical and simulation results; Blocking probability versus traffic load.

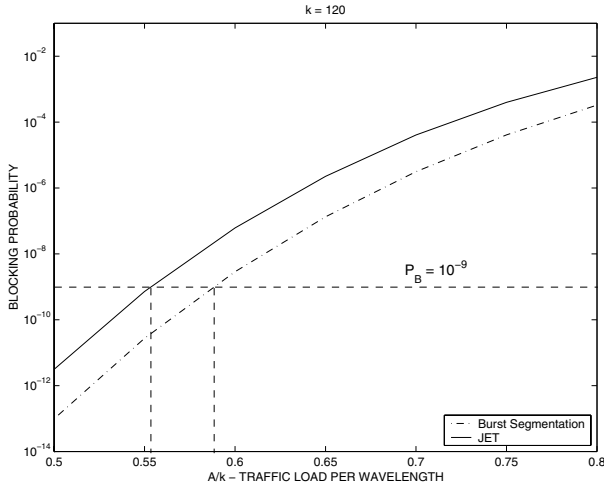


Fig. 3. Comparison of JET vs. Burst Segmentation for 120 wavelengths.

D. Performance Comparison of JET and Burst Segmentation

Figure 3 compares the performance of JET and Burst Segmentation for $k = 120$ wavelengths. For such a large system we see that loss rates of 10^{-9} can be achieved at quite high utilisations, around 0.55 for JET and 0.59 for Burst Segmentation. Furthermore, segmentation allows a 7% improvement in utilisation for the same low loss rate.

Having established the burst and packet loss rates for both JET and Burst Segmentation, we are interested in the relative benefit of Burst Segmentation over JET. A very simple expression for the ratio of blocking probabilities can be obtained under very light load conditions, when $k \gg A$. We use (1) and (2) to calculate the ratio

$$\frac{P_B(k, A)}{P_{BS}(k, A)} = \frac{P_B(k, A)}{E[L]/A} \quad (5)$$

We notice from (4) that $P(k+j) = [A/(k+j)] \cdot P(k+j-1)$, $j \geq 1$, so that if $k \gg A$ then $P(k+1) \gg P(k+2) \gg$

$P(k+3) \gg \dots$, so that we can write

$$E[L] \approx P(k+1). \quad (6)$$

$P_B(k, A)$ is the proportion of work lost in a system without burst segmentation. $P(k+1)/A$ is the proportion of work lost when burst segmentation is used assuming $P(i)$ is negligible for $i > k+1$, namely, the overall proportion of work lost is very small. This will happen if $k \gg A$. The ratio between the two is

$$\frac{P_B(k, A)}{P(k+1)/A} = \frac{(k+1)}{e^{-A} \sum_{m=0}^k \frac{A^m}{m!}}. \quad (7)$$

Hence

$$\lim_{k \rightarrow \infty} \frac{P_B(k, A)}{P(k+1)/A} = k+1. \quad (8)$$

Note that the simple result of (8) applies only to cases where the load is unrealistically low.

III. NETWORK ANALYSIS

A. Fixed Point Approximation

Whilst the single node models of Section II give much insight into the performance of OBS, they cannot capture network-related effects such as increase in load due to unsuccessful bursts which still consume resources along the route until they are blocked, and reduced load due to blocking of bursts earlier in their routes. A reduced load, fixed point approximation technique has been introduced in [13] for analysis of OBS networks, taking account of network-related issues.

In this framework we consider a network with J directional links. Each link $j \in \{1, \dots, J\}$ is capable to transmit data only in one fixed direction and serves up to N_j concurrent logical channels using WDM.

A route $\mathbf{r} = (r_1, r_2, \dots, r_n)$ having n hops is an ordered set of links that connect the source node to the destination node. Let \mathcal{R} be the set of all possible routes. We assume that bursts offered to route \mathbf{r} arrive according to a Poisson process with rate $\lambda_{\mathbf{r}}$ and all arrival processes are independent. A burst offered to route \mathbf{r} uses a single wavelength from each link along the route until the first link where it is being blocked or until it exits the network. That is, if the burst is first blocked by link r_j it uses a single wavelength channel from links r_1, r_2, \dots, r_{j-1} in succession. We further assume that burst transmission times are independent and exponentially distributed and we denote by μ_j the transmission rate of link j .

We denote by $\mathbf{B} = (B_1, B_2, \dots, B_J)$ the vector of stationary link blocking probabilities. Given the difficulty in obtaining exact mathematical results for this problem, the model assumes as in [6], [7], [8] and [9] that each blocking event occurs independently from link to link along any route. It was shown in [13] that under stationary conditions the blocking probability of an arbitrary burst offered to route \mathbf{r}

can be calculated by computing the reduced load ρ_j offered to link j :

$$\rho_j = \mu_j^{-1} \sum_{\mathbf{r} \in \mathcal{R}} \lambda_{\mathbf{r}} \prod_{i=1}^J (1 - I(i, j, \mathbf{r}) \cdot B_i), \quad (9)$$

where $I(i, j, \mathbf{r})$ equals 1 or 0 depending whether or not $i, j \in \mathbf{r}$ and link i strictly precedes link j along route \mathbf{r} , respectively.

Furthermore, the independence assumption implies that the offered load to each link j is a Poisson process with rate ρ_j . Thus, the blocking probability is given by (1), i.e.

$$B_j \stackrel{\text{def}}{=} P_B(N_j, \rho_j). \quad (10)$$

Combining equations (9) and (10) yields the following Erlang Fixed Point (EFP) equations satisfied by the approximate link blocking probabilities,

$$B_j = P_B\left(N_j, \mu_j^{-1} \sum_{\mathbf{r} \in \mathcal{R}} \lambda_{\mathbf{r}} \prod_{i=1}^J (1 - I(i, j, \mathbf{r}) \cdot B_i)\right). \quad (11)$$

Resolving the vector \mathbf{B} from the EFP equations (11) and invoking the independence assumption again, the approximate blocking probability of bursts offered to route \mathbf{r} , $B(\mathbf{r})$, satisfies

$$B(\mathbf{r}) = 1 - \prod_{i \in \mathbf{r}} (1 - B_i),$$

and the blocking probability of an arbitrary burst B , satisfies

$$B = \frac{1}{\Lambda} \sum_{\mathbf{r} \in \mathcal{R}} \lambda_{\mathbf{r}} \cdot B(\mathbf{r}),$$

where $\Lambda = \sum_{\mathbf{r} \in \mathcal{R}} \lambda_{\mathbf{r}}$.

Notice that the OBS reduced load offered to link j as given in equation (9) is larger than $\mu_j^{-1} \sum_{\mathbf{r} \in \mathcal{R}} \lambda_{\mathbf{r}} \prod_{i \in \mathbf{r} \setminus \{j\}} (1 - B_i)$, the reduced load offered to link j in a conventional circuit switching network.

It was demonstrated in [13] that the fixed point equations (11) can be solved for the blocking probabilities \mathbf{B} by a successive substitution procedure, and although uniqueness of the solutions has not been established, the existence of a fixed point has been shown and in numerical studies the procedure is always observed to converge to a unique fixed point. By Theorem 1 of [13], it was shown that an upper and lower bound on the vector of blocking probabilities can always be established.

The definition of the link blocking probabilities (10) can be replaced with other expressions for systems wherein the $M/M/k/k$ model is not appropriate. To analyse Burst Segmentation networks in this framework we replace Equation (10) with (2) above to define $B_j = P_{BS}(N_j, \rho_j)$ and form the fixed-point equations from this expression. Convergence to the upper and lower bounds is also guaranteed so long as the transformation defined by the fixed point equations is decreasing.

Route Name	Route hops
R_1	1→4→6→5→8→10
R_2	2→3→5→6→7
R_3	2→7→9→12→13
R_4	3→5→8→13
R_5	5→6→7→9→12
R_6	8→10→11→12→13
R_7	10→8→5→6→4→1
R_8	7→6→5→3→2
R_9	13→12→9→7→2
R_{10}	13→8→5→3
R_{11}	12→9→7→6→5
R_{12}	13→12→11→10→8

TABLE I
NSFNET ROUTES

B. Numerical Results

We used the *NSFNET backbone network* topology depicted in Fig. 4 to compare the results of the reduced load fixed point approximation for both JET and Burst Segmentation. The network topology comprises 13 OBS switches and 32

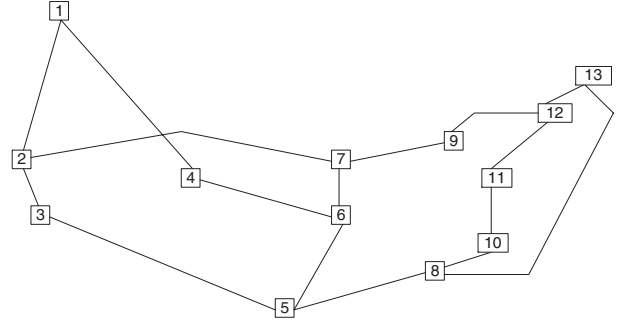


Fig. 4. NSFNET backbone network (T3, 45 Mb/s, April 1995).

unidirectional fibre links, each comprising of 8 wavelength channels. We evaluated the blocking probabilities of 12 routes defined in Table I. The selected routes represent a variety of path lengths, link sharing degrees and mixtures of external and on-route internal traffic processes. All routes are shortest paths, except for R_3 and R_7 that are selected to obtain better route diversity.

Figure 5 validates the approximation for the overall blocking probability using various load values for JET and for Burst Segmentation. Here, we considered symmetric traffic scenarios where all routes are offered the same burst external arrival rate, i.e. $\lambda_{\mathbf{r}} = \lambda$ for all \mathbf{r} . The channel capacity and burst length are set to yield a burst service rate of $\mu = 25$ bursts per second. Similarly to the single node case, the simulation results are presented with their respective 95 % confidence intervals based on the Student's t-distribution. It can be seen that the approximation provides accurate predictions of overall blocking probabilities and that burst segmentation provides significant benefit in overall blocking.

Note that results for very low blocking probability (e.g. 10^{-6}) are unobtainable for network simulations due to the large state space. Therefore, the validation of our approxi-

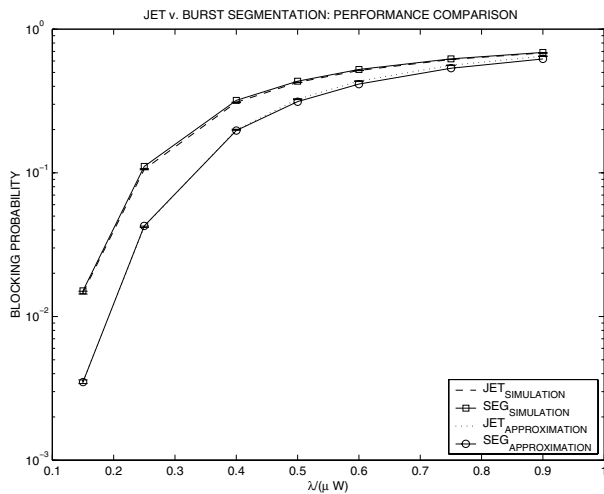


Fig. 5. Overall Blocking Probability: Simulation vs. Analysis for JET and Burst Segmentation.

Routes \ λ	$\lambda = 5$ /sec		$\lambda = 10$ /sec	
	JET $\times 10^{-9}$	Seg. $\times 10^{-9}$	JET $\times 10^{-6}$	Seg. $\times 10^{-6}$
R_1	251	27.8	35.9	4.98
R_2	251	27.8	35.9	4.98
R_3	32.7	3.64	5.62	0.624
R_4	21.8	2.43	3.75	0.417
R_5	261	29.0	37.73	5.19
R_6	21.9	2.43	3.76	0.418
R_7	251	27.8	35.9	4.98
R_8	251	27.8	35.9	4.98
R_9	32.7	3.64	5.62	0.624
R_{10}	21.8	2.43	3.75	0.417
R_{11}	261	29.0	37.73	5.19
R_{12}	21.9	2.43	3.76	0.418
Overall	140	15.5	20.4	2.77

TABLE II

ROUTE BLOCKING PROBABILITIES WITH JET AND SEGMENTATION - APPROXIMATION

matation is only performed for blocking probability values of 10^{-3} and above. This is a very good reason to have analytical results. Only by using analytical results we are able to compare between the performances of JET and Burst Segmentation in cases of low blocking probability.

Table II shows the blocking probability for each route under low load conditions of $\lambda = 5$ and $\lambda = 10$ bursts per second, as calculated by the approximation. Again, segmentation provides large benefits on all routes, and the overall improvement is almost an order of magnitude.

IV. CONCLUSION

We have provided an analytical comparison of JET and Burst Segmentation for the single node, single link scenario, and we have shown that in the limit of low load, $k \gg A$, Burst Segmentation offers a factor of $k + 1$ improvement, which can be more than two orders of magnitude for foreseeable dense WDM systems. We have extended these two models using the reduced load fixed point approximation for network analysis

and shown that segmentation again provides significant benefits on a per-route and an overall network blocking probability basis.

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