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Abstract

Today, OCS (Optical Circuit Switching) is still the only mature technology for optical transfer, even if it suffers from its coarse granularity under dynamic and bursty scenarios. It remains the case in spite of the grooming technologies, together with the VCAT (Virtual conCATenation) and LCAS (Link Capacity Adjustment Scheme) enhancements. OBS (Optical Burst Switching) has been proposed to improve the resource usage efficiency in unfavorable scenarios to OCS, e.g., bursty traffic.

Yet far from being mature, OBS is a bufferless packet oriented switching paradigm. Such a bufferless paradigm is still unusual. We show in this paper that the traffic in the core network conforms to the yet unrevealed OBS transparency property: Switching operations do not modify the OBS traffic profile. This entails that the emission process completely defines the traffic profile in OBS core networks.

Following the disclosure of the OBS transparency property, we investigate the resulting OBS traffic in core networks and propose an accurate traffic model. Empirical observations of various configurations have highlighted some impacting factors and favorable configurations for reducing burst losses and, therefore, maximizing the throughput. Based on the conclusions of the analysis, we elaborate new recommendations for burst traffic aggregation design so that friendly aware traffic is emitted.

Résumé

Bien que la commutation de circuits optiques (OCS) soit la seule technologie mature pour le transport de données sur fibres optiques, ses performances se dégradent dans le cadre de scénarios à trafic variable. La commutation de rafales (OBS) a été proposée pour améliorer l'utilisation des resources dans des scénarios dynamiques.

OBS est plutôt atypique, parce qu'il est orienté paquets et ne nécessite pas de mémoire. Cette transparence optique augmente la responsabilité du processus d'émission car le trafic, une fois émis, ne sera plus modifié dans le cœur.

Nous observerons le trafic dans le cœur pour mettre en évidence certaines configurations qui permettent de réduire le taux de perte. Cette étude nous permettra de formuler de nouvelles recommandations relatives à la configuration du processus d'émission.

1 Introduction

Data transit through numerous networks and are manipulated to fit with numerous protocols all along their journey between end-users. In order to provide a good characterization of network performances, traffic engineering should take, as much as possible, the statistical properties of the resulting flows into account, in the network design step. The traffic profile has a high impact on the network performance and therefore requires a particular attention.

Nowadays, optical networks cannot be sidestepped. Optical deployment is a hot topic, although using more efficiently the tremendous offered capacity becomes increasingly complex due to technological constraints. Today, Optical Circuit Switching (OCS) is the only mature technology, but Optical Burst Switching (OBS) has been proposed [1] as an attractive alternative to OCS in unfavorable scenarios (see, e.g., [2]).

In OBS networks, data go through four steps: Aggregation, access to optical medium, transit toward the destination and disaggregation. Burst aggregation is an electrical process performed in access nodes. It reduces the signaling overhead by grouping several IP packets into a single burst. In core networks, bursts from different sources share the same set of wavelengths. As buffering is not possible in OBS core networks, data are pre-signaled (Just Enough Time - JET - protocol) and switched all-optically. However, collisions among bursts cannot be fully avoided: in such a case, one (or more) burst is simply rejected. Hence, the most commonly used performance parameter of OBS networks is the loss rate. In order to fully understand the deep origins of burst losses, it is worth investigating further the characteristics of the burst arrival process throughout all the traversed nodes.

Usually, analyses are performed on the basis of the Poisson assumption: As the network mixes a very large number of different flows, according to statistical multiplexing, the resulting incoming flows of any node can be represented, with a reasonable accuracy, by a Poisson process. It has the advantage to offer simple closed expressions for various performance criteria, and especially the celebrated Erlang-B loss formula. Although it can be a reasonable assumption at the entrance (many users slightly contribute to the overall load), the argument based on the assumption that the traffic is composed of an infinity of sources is irrelevant in OBS core networks.

An improvement can be proposed by taking into account the finite number of sources, based on the same statistical assumptions, and it leads to the so-called Engset loss formula (see, e.g., [3,4,5]). Multi-rate variants of these formulas have been proposed. In [6], a simple loss approximation formula is proposed for a limited number of non-uniform sources.

However, the OBS technology relies on several specific characteristics, which contribute to invalidate the classical loss models. Advanced models have been proposed with various equipment and assumptions (e.g., [7,8,9]), but none of them include the properties disclosed in this paper.

Firstly, we observe that the switching operations in an OBS network do not modify the source traffic profile, which keeps the same statistical characteristics all along the path, regardless of the number of traversed switches. We call this phenomenon the *OBS transparency property.* It implies that the source behavior completely defines the traffic profile in a core network.

Secondly, as an immediate consequence of the transparency property, We show that the loss rate, at any given node, can be accurately approximated by the one in a simplified star topology where intermediate nodes are ignored.

Thirdly, we disclose the following new *Loss Independent Arrival (LIA) property*: As the emission of a burst is independent of the fate of the previous bursts, the transparency property entails that, in a core network, a burst arrival has no impact on the arrival of the next one. We include the LIA property in a more accurate model of the traffic, called LCH$^+$, in an OBS core network.

The paper is organized as follows. The problem is stated in Section 2. In Section 3, we discuss the transparency and the LIA properties and their impacts on the traffic profile in the core. A finite source model, called LCH$^+$, derived from the LCH model of [3, 10], and which fully takes advantage of the OBS transparency property and the Loss Independent Arrival property, is presented in Section 4. It is much more accurate than the commonly used models, which we recall at the beginning of the section. Experiments are reported in Section 5 where the "star approximation“ and the new LCH$^+$ traffic model are illustrated. We then highlight several observations on the OBS characteristics to be taken into account in an efficient OBS network design. Conclusions are drawn in Section 6.

2 Statement of the Problem

In OBS networks, the largest degrees of flexibility are in the access nodes. Aggregation process and burst emission highly impact the traffic profile in the core network. In this paper, we propose to deeply investigate the dropping process in an OBS core network in order to evaluate the influential parameters that can be controlled at the burst emission.

The task of a core OBS switch is to transmit incoming traffic toward the next OBS switch. We will call a “stream” the traffic arriving from an input port and requesting the use of an outgoing link. Due to statistical multiplexing, the traffic of a stream is not restricted to a single connection.

In order to facilitate the reading of the paper, let us clarify some correspondences of the OBS technology and the classical teletraffic terminologies. In core switches, the clients (bursts) are submitted by input ports. A source must thus be conceived as an incoming stream, regardless of the connections involved in it. We denote by b the average size of the bursts and Λ their arrival rate. The bursts are served by an output port of the destination link (i.e., a wavelength) of transport capacity C, in a time b/C, equivalent to a “rate” $\mu = C/b$.

We will assume that every wavelength has the same transport capacity (C), that the optical links have all the same number W of wavelengths, and that full all optical wavelength conversion is available at every node, thus providing W servers to the clients (any wavelength of the link of concern can be used). This implies that, if we denote by d_v the connectivity of node v, i.e., its degree, no more than $W \times d_v$ sources can be involved in the model of node v.

3 Some important features of OBS traffic

The traffic, as observed inside OBS networks, has several peculiar features, making inappropriate a direct use of most classical teletraffic results. We investigate two of them in this section.

3.1 OBS Transparency Property

The first important feature can be expressed by “flows of different connections never mix”. In a network with buffers, mixing different flows modifies their characteristics. Indeed, multiplexing different flows, which usually “smoothes” their characteristics, has absolutely no effect in an OBS core network. This could be of some importance for self-similar traffic. However, in this exploratory study, we restrict our attention to memoryless arrival processes. The influence of more elaborated arrival processes is left for further study.

In an OBS network, the switches are preconfigured so that the data plane is switched all optically. The bursts thus cut-through without being delayed. It entails that: *(i)* the gap between two successive bursts is not affected by a node traversal and each sequence of bursts remains unchanged when going through a node – except that some bursts can be discarded due to unresolved collisions ; *(ii)* the travel time between two nodes determines the propagation delay ; it only depends on the propagation speed of the light in an optical fiber ($200,000$ km.s^{-1}) and the total traveled distance, whatever the number of traversed switches.

The implication is significant. Consider, for instance, the tree topology represented in Figure 4. Under the assumption that any outgoing link (links are directed upwards) has enough wavelengths to solve every

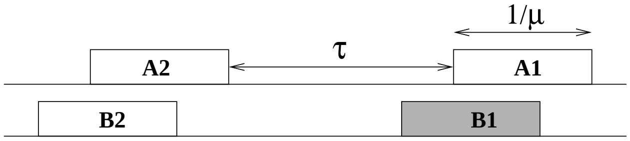


Figure 1: Core Network Traffic Arrival

contention (i.e., the number of overlapping bursts is always lower than the number of wavelengths), the traffic observed on link $r \rightarrow d$ is identical to the traffic observed on a derived star topology where each leave is directly connected to r with the same path length. Indeed, if two bursts overlap somewhere in the tree, they will overlap until the last link. As the travel time is not modified in the star topology, they also overlap in the star topology. Reciprocally, if two bursts overlap in the star topology, then they would overlap somewhere in the tree, until the last link.

Now if, at some given time, the overlapping bursts outnumbers the number of wavelengths, one (or more) burst must be dropped. In the star topology, loss occurs exclusively at r whereas it can occur at any node in the tree. The bursts are thus not dropped in the same order and the loss probability is not necessarily the same. In Section 5, we evaluate the accuracy of the star approximation of any given tree.

3.2 Loss Independent Arrival Property

The bursts aggregated by a source of traffic are emitted by a network access point without knowledge about the fate of the previously sent bursts. The only information comes through acknowledgments, arriving at arbitrary intervals, which are too large to be of any help for real time traffic management. In particular, a source that sends bursts, keeps on sending bursts even if some of them are rejected due to collision.

Because of the transparency property, such a behavior remains unchanged in the core network: The arrival of a burst submitted by an input port to a set of output ports is independent of the state of the output ports and the fate of the previous bursts. In addition, the bursts submitted by a given input port cannot overlap since they have been served by the same output port in the previous node. As a consequence, the traffic arrival in an OBS core switch can be described by the diagram on Figure 1. The input port either submits a burst of average duration $1/\mu$ or waits τ time units before submitting the next burst. Due to statistical multiplexing, several connections can be superimposed and an input port can submit bursts from a large number of connections. Hence, the burst submission process of an input port is a mix of several arrival processes. In the context of our study, it can be approximated by a Poisson process if the number of multiplexed connections is large enough.

We denote by $\lambda = 1/\tau$ the arrival rate of an idle input port. The burst submission will remain the same, whether the burst is dropped or served. In the example, burst B_1 is dropped, but this event has no impact on the next arrival. In the sequel, an input port is referred to as *active* for the whole duration of the burst, whether the burst is successfully transmitted or not.

When we observe a group of N input ports, a direct consequence of the above remark is that the number of active ports is distributed according to a binomial law:

$$P(n) = \binom{N}{n} \alpha^n (1-\alpha)^{N-n}, \tag{1}$$

where α stands for the load offered by a source:

$$\alpha = \frac{1}{\mu(1/\mu + \tau)} = \frac{1}{1+\tau\mu}.$$

4 Traffic Models and Loss Approximation

4.1 Previous Models and Loss Approximations

The Poisson assumption has been widely used. It describes a source of load A as an infinity of sources of load ε, summing to A. Under this assumption, the loss probability is given by the Erlang-B Formula [4]. The simplicity of the Erlang-B loss formula allows its use in optimization heuristics (e.g., [11]).

The Poisson assumption is, however, irrelevant in an OBS core network since an OBS core switch multiplexes a finite (usually small) number of incoming links. That means that Poisson assumptions must be definitely banned, as already observed, see, e.g., [6]. Indeed, it is a classical result that the Erlang formula must be replaced by the Engset scheme [4, 3], which takes advantage of the finite number of sources.

The Engset distribution is derived from the binomial distribution. It describes a system with a limited number of sources that switch between the "idle" and "busy" states. The source can submit a client only when it is in the "idle" state. A client is rejected if its arrival occurs while all servers are busy in which case, the corresponding source immediately switches to the "idle" state. A closed formula has been derived to express the loss probability of such a system [4].

In telephone systems, for instance, the Engset scheme holds for access (concentration) nodes. Inside the network, as more and more flows are superimposed, the Poisson assumption is valid again, and so is the Erlang formula. OBS networks hardly conform to this scheme, because the usual multiplexing operations have no effect on the traffic profile, even in core networks.

According to the input port behavior discussed in Section 3.2, the source must stay "busy" for the whole duration of a burst, whether it has been dropped or served. The source then switches to "idle" state and can submit the next burst. In the next section, we propose an accurate description of the input port behavior.

Both Erlang-B and Engset loss formulas assume uniform traffic. Variations have been proposed to handle the cases where sources do not equally contribute to the load. Unfortunately, the resulting formulas are often computationally expensive (see, e.g., [5]). In [6], a simple approximation is proposed and provides a quite accurate prediction of the loss with Poisson distributed arrivals as long as the number of sources remains low.

4.2 LCH$^+$ Model

In this section, we propose a "finite source" model for the traffic in an OBS core network that conveys the behavior of the LIA property. We called it LCH$^+$ as it differs slightly from the "Lost Call Held" model described in [3, 10]. In the remainder of this section, we assume exponentially distributed burst sizes and a source denotes an incoming port. Let $\alpha_i = 1/(1 + \tau_i \mu_i)$ and $\lambda_i = 1/\tau_i$, where λ_i is the arrival rate of an idle source. We distinguish two cases.

4.2.1 Uniform Case

Figure 2 represents the model of an outgoing link, with W wavelengths, of N identical sources.

The state (i, j) represents the configuration where i clients are currently served whereas j clients are being dropped. Hence, $(i + j)$ sources are busy and $N - (i + j)$ sources may submit a client (the arrival rate is $(N - (i + j))\lambda$). If $i < W$, the next client is served, and the system moves to state $(i + 1, j)$. If $i = W$, all servers are in use and the next burst is dropped. Whereas an Engset system would remain in state (i, j), the LCH$^+$ model blocks the source by switching to state $(W, j + 1)$.

At a client departure, an active source switches to state *idle*. The departure rate of served clients is $i\mu$ (in that case, a server is freed and the next state is $(i - 1, j)$) and $j\mu$ for bursts being dropped (the next state is $(i, j - 1)$).

The model remains scalable as the number of states is in the order of $N \times W$. The resolution provides the probability $P_{i,j}$ for the system to be in state (i, j). A client is rejected if it is submitted while all servers

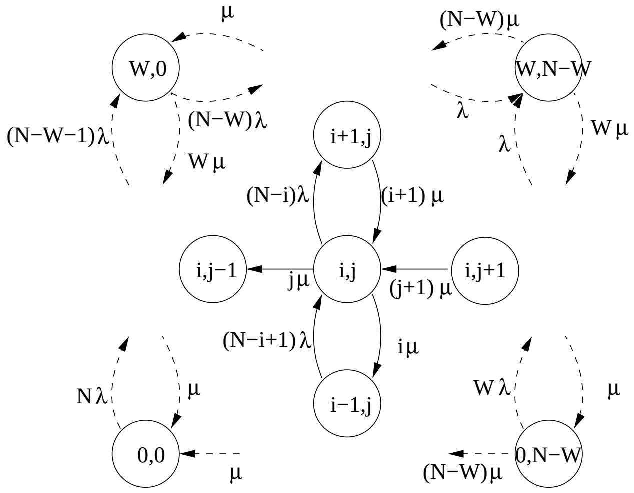


Figure 2: LCH model (uniform traffic)

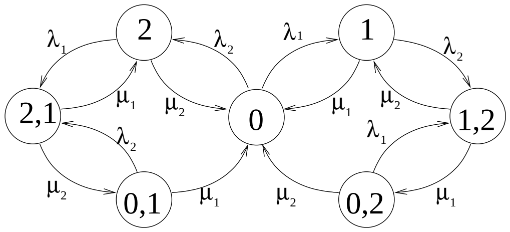


Figure 3: LCH model with two sources and one wavelength

are busy, i.e., any state $(W, j), j \in [0, N-W]$. The loss probability is thus the ratio of the rejection rate over the total submission rate:

$$\mathrm{LCH}^{+}(\alpha, N, W) = \frac{\sum\limits_{i=0}^{N-W-1} (N-(W+i))P_{W,i}}{\sum\limits_{w=0}^{W} \sum\limits_{i=0}^{N-W-1} (N-(w+i))P_{w,i}}. \tag{2}$$

4.2.2 Non-Uniform Case

The non-uniform case is much more complex, but can be easily represented in the case of one server and two sources (Figure 3). The loss probability of connection i can be expressed as follows:

$$\mathrm{LCH}(\alpha_i, 2, 1) = \frac{P_j}{P_0 + P_{0,j} + P_j}, \qquad \text{where } j = 2 - i. \tag{3}$$

5 Numerical Results

In this section, we conduct various experiments, through simulations, in order to investigate further the OBS network transparency property (Section 5.1), the LCH^{+} model (Section 5.2), the burst size (Section 5.3) and the load balancing (Section 5.4) and their impacts on the OBS network performances, and in particular on the burst losses.

Throughout this section, W denotes the number of wavelengths per link, assuming each one has an OC-192 ($C = 10$ Gbps) transport capacity. A source is called a stream and represents the incoming flow at a given input port (wavelength of an incoming fiber). The average size of the bursts of source i is denoted by b_i, and their average length is $1/\mu_i = b_i/C$. Λ_i is the arrival rate of bursts of stream i, τ the idle time between two successive bursts of connection i ($1/\Lambda_i = 1/\mu_i + \tau_i$), α_i the load of connection i ($\alpha_i = 1/(\mu_i \tau_i + 1)$), and last, a_i the corresponding bandwidth request ($a_i = \alpha_i C$). We also use A to denote the overall data rate of incoming streams.

5.1 Star Approximation

We first test the quality of the approximation obtained with the star topology derived from the tree represented in Figure 4. Each leaf sends identical traffic to node d (Poisson arrival of bursts of constant size arriving with exponentially distributed τ_i). In the uniform scenario, the overall load is uniformly distributed among all sources whereas in the unbalanced scenario, the load is distributed so that $a_i = 2 \times a_{i-1}$. The bursts are processed in the order of their arrival and each link has $W = 3$ wavelengths. Figure 5 reports the overall loss probability of both scenarios on the tree, and the derived star topologies. The initial overall load of 8 Gbps is tuned by a multiplicative coefficient (α).

The star topology is shown to provide an accurate estimation of the loss probability obtained with the tree topology in both balanced and unbalanced scenarios. A very small gap appears under very high load (i.e., when the loss probability is unacceptably high). Except for those scenarios of limited interest, the star topology can be used as a faithful approximation. It can considerably simplify the studies and reduce the simulation speeds, as it reduces the number of iterations of the fixed point method.

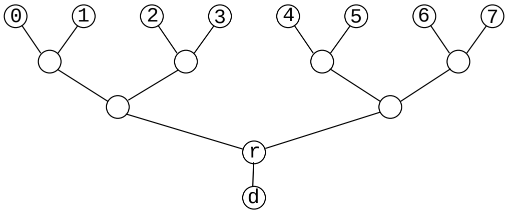


Figure 4: A 3-stage binary tree

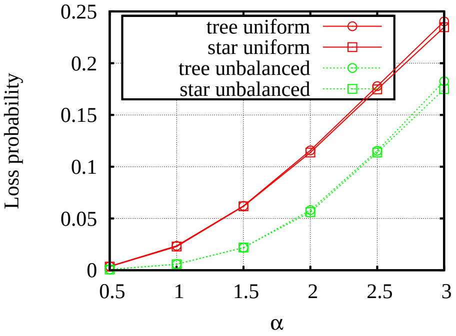
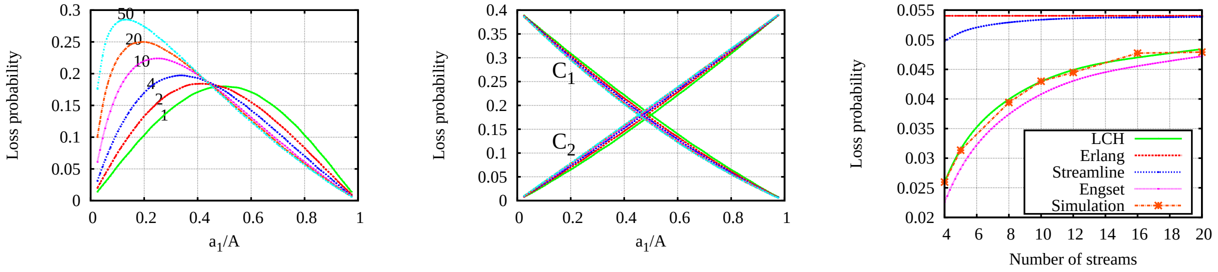


Figure 5: Loss Probability on Tree and Star Topologies (Unbalanced Scenario)

5.2 LCH$^+$ Accuracy

We perform a similar experiment to the one proposed in [6] to compare the streamline formula with the LCH$^+$ model and to analyze the impact of the number of sources. We use a system with 2 wavelengths per link and an overall load (4 Gbps) uniformly distributed among the input streams. The loss probabilities predictions are illustrated on Figure 6(c). The streamline formula achieves a good prediction with Poisson distributed arrivals [6]. However, with the source behavior described in Section 3, it suffers from the Poisson



(a) Influence of b_2 on overall loss ($b_1 = 1$) (b) Influence of b_2 on connection loss ($b_1 = 1$) (c) Influence of the number of streams

Figure 6: Influence of Aggregation Parameters on Loss Probability

assumption and quickly overestimates the loss rate similarly to the Erlang formula. The Engset formula is closer to the real behavior but underestimates the loss, whereas the proposed LCH$^+$ model is more accurate.

Observation 1: At constant load, as in classical queuing models, a smaller number of streams improves the performance.

5.3 Impact of the Burst Size

We consider two streams S_1 and S_2 of load a_1 and a_2 in a system with one wavelength ($W = 1$). The overall load A stays constant and equal to 2 Gbps, but the contribution of each connection varies (x-axis represents $\dfrac{a_2}{a_1 + a_2}$).

Several sets of experiments are plotted on Figures 6(a) and 6(b). For each experiment, $b_1 = 1$ and b_2 is increased. The values of b_2 are reported on the corresponding curve on Figure 6(a) where the overall loss probability is depicted. The line styles of Figure 6(a) are preserved in Figure 6(b) where the loss probability of the two connections is represented.

With equal burst sizes, the worst case is obtained for the balanced configuration where $a_1 = a_2$. Increasing traffic unbalance improves overall performances. The improvement is due to the reduction of the loss probability of the dominant stream with the detriment of that of the soft stream.

The size ratio has no significant impact on the individual source loss probability, but clearly influences the overall performances. At equal load, the arrival rate decreases as the burst size increases. Thus, the overall dropping probability is more impacted by the stream with the shortest bursts. A consequence of this variation is that the worst case moves away from the configuration with equal loads.

Observation 2: The worst case loss probability increases with the gap between b_2 and b_1.

Additional experiments on the burst size (for a given value of b_2/b_1) and its distribution (exponential and constant distribution have been compared) led to the following observations (results are not shown due to space restriction):

Observation 3: For any fixed value of b_1/b_2, the distribution of the size of the bursts has no influence on the performances. In particular, constant and exponential distribution of the size of bursts entail the same performances.

Observation 3 is important since the constant distribution is a better approximation of the distribution observed in [12] than exponential distribution.

5.4 Impact of the Load Balancing

We consider two classes of sources S_1 and S_2, according to their traffics: the load of S_1 (resp. S_2) is a_1 (resp. a_2). There are respectively with N_1 (resp. N_2) streams of type S_1 (resp. S_2).

5.4.1 Impact of the Number of Dominant Streams

We first set a_1 = 40Gbps and a_2 = 20Gbps and analyze the influence of the number of streams involved in S_1 and S_2 (Figure 7).

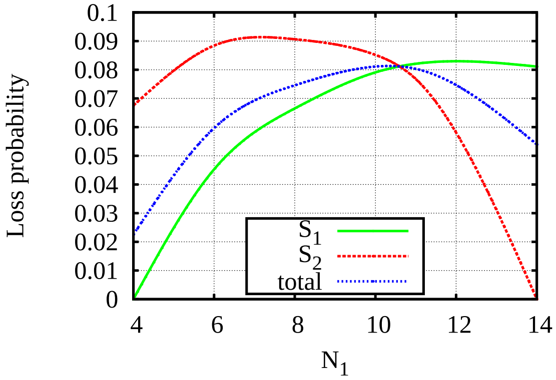


Figure 7: Loss probability vs N_1 ($a_1 = 40Gbps$)

Observation 4: The homogeneous state where the load is uniformly distributed among the streams is the worst case configuration ($N_1 = 11$ in our experiments).

If N_1 is decreased, a_1 is concentrated among less streams and consequently, their load increase. As the streams of S_1 become dominant over the streams of S_2, their service is improved. The overall performances are improved as well, as the streams of S_1 represent the major part of the overall traffic. On the opposite, the service of streams of S_2 is degraded.

Observation 5: With unbalanced traffic repartition, the dominant streams are better served than the soft streams.

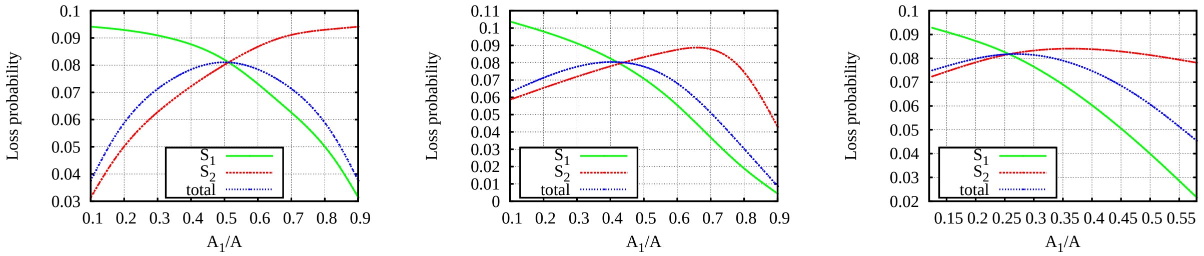
Note, however, that when the traffic is strongly unbalanced ($N_1 \leq 4$), services of both S_1 and S_2 are improved. The reason is that, streams from S_1 use no more than N_1 wavelengths at a time. Thus, decreasing N_1 increases the wavelength availability for S_2 with a reduced load. The same analysis holds with a large value for N_1: Few streams of S_2 outrageously dominate, so that several wavelengths are available for soft streams of S_1.

Observation 6: Soft streams can also benefit from an unbalanced repartition, more likely if the number of dominant streams is small compared to the number of wavelengths.

5.4.2 Impact of the gap between dominant streams and soft streams

We set $N_1 \in \{4, 6, 8\}$ and tune a_i within the constraint $A = 60$ Gbps. The symmetric case ($N_1 = 8$, see Figure 8(a)) confirms observations 4 and 5. Note that Observation 6 does not hold: The soft connections are never improved. The reason is that the number of dominant streams equates the number of wavelengths. In that case, the soft streams always have to challenge the dominant ones.

If $N_1 = 6$ (Figure 8(b)) or $N_1 = 4$ 8(c), Observation 6 is verified. The soft stream improvement is more obvious if the dominant streams are more concentrated: The maximum loss rate is lower and achieved at higher rate. The previous explanation holds: the lower N_1, the less wavelengths S_1 can occupy. The performance of the soft streams is thus related to the ratios N_1/N_2, N_2/W and a_1/a_2.



(a) $N_1 = 8, N_2 = 8$ (b) $N_1 = 6, N_2 = 10$ (c) $N_1 = 4, N_2 = 12$

Figure 8: Influence of the Traffic Balancing

6 Conclusions

In this paper, we discussed the traffic evolution in OBS networks. We first disclosed the OBS transparency property in bufferless networks: Switching operations do not modify the traffic profile. It means that the traffic profile in a core OBS network is completely determined by the emission process at the sources. Hence, the loss estimation at an internal node may be greatly simplified, thanks to the accurate approximation provided by the "star" approximation of a tree network.

We also investigate the Loss Independent Arrival property: The burst arrival in a core node is independent of the fate of previous bursts. As this property makes the use of classical models inappropriate, we proposed a new model that is much more accurate, the LCH$^+$ model.

Several configurations have been studied which help bringing to light interesting properties. Firstly, the performances are non-sensitive to the distribution of burst sizes, but heterogeneous average burst sizes of contending sources degrade the performances. This promotes the use of bursts of constant size. It more likely occurs when the aggregation queues are highly loaded. Secondly, the performances are improved if the number of sources (and consequently the number of aggregation queues) is decreased. This observation must be taken into account when designing a core network and defining the classes of services. Finally, we highlighted the positive impact of traffic unbalance on the overall network performances.

Note that all favorable configurations identified in this paper are more likely encountered with a reduced number of aggregation queues depending of the MAC in use and the number of sources.

References

[1] M. Yoo, M. Jeong, and C. Qiao, "A new optical burst switching (OBS) protocol for supporting quality of service," in *SPIE*, vol. 3531, November 1998, pp. 396–405.

[2] X. Liu, C. Qiao, X. Yu, and W. Gong, "A Fair Packet-Level Performance Comparison of OBS and OCS," *Optical Fiber Communication Conference*, p. 3, 2006.

[3] R. Syski, *Introduction to Congestion Theory in Telephone Systems*. Elsevier, 1986.

[4] G. Fiche and G. Hébuterne, *Communicating Systems & Networks: Traffic & Performance*. Kogan Page Science, 2004.

[5] I. Moscholios and M. Logothetis, "Engset multi-rate state-dependent loss models with QoS guarantee," *International Journal of Communication Systems*, vol. 19, no. 1, pp. 67–93, 2006.

[6] M. Phùng, K. Chua, G. Mohan, M. Motani, and T. Wong, “The streamline effect in OBS networks and its application in load balancing,” in *2nd International Conference Broadband Networks*, October 2005, pp. 304 – 311.

[7] C. Hsu, T. Liu, and N. Huang, “Performance analysis of deflection routing in optical burst-switched networks,” in *IEEE Annual Joint Conference of the IEEE Computer and Communications Societies - INFOCOM*, vol. 1, 2002, pp. 66–73.

[8] Y. Chen, H. Wu, D. Xu, and C. Qiao, “Performance analysis of optical burst switched node with deflection routing,” in *Communications, 2003. ICC'03. IEEE International Conference on*, vol. 2, 2003.

[9] M. Neuts, Z. Rosberg, H. Le Vu, J. White, and M. Zukerman, “Performance Analysis of Optical Composite Burst Switching,” *IEEE COMMUNICATIONS LETTERS*, vol. 6, no. 8, 2002.

[10] A. Viterbi, *CDMA Principles of spread spectrum communication Addison-Wesley wireless communications series.* Addison-Wesley Pub, 1995.

[11] J. Teng and G. Rouskas, “Traffic engineering approach to path selection in optical burst switching networks,” *Journal of Optical Networking*, pp. 759–777, 2005.

[12] X. Yu, Y. Chen, and C. Qiao, “A study of traffic statistics of assembled burst traffic in optical burst switched networks,” in *Proceedings of Opticomn*, vol. 4874, 2002, pp. 149–159.