Analysis of OBS burst scheduling algorithms with stochastic burst size and offset time

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***Abstract*— One of the key factors in Optical Burst Switching Networks is the scheduling algorithm that is used in the switches to allocate the incoming bursts to a wavelength. In this paper we evaluate the most well-known scheduling algorithms assuming a realistic case of non-deterministic offset times and burst sizes. Many interesting conclusions can be drawn from this approach. First, the scheduling algorithms' performance with respect to the burst loss ratio is not highly influenced by the burst size distribution, whereas the offset time variability has some influence. Secondly, if the target loss rate is small (10^{-5}) the performance of the different scheduling algorithms is roughly the same. On the other hand, extensive evaluation of the algorithms' computational cost is also performed to conclude that, at low loss rates, a simple First-Fit with void filling algorithm provides the same result than a more complex void filling algorithm, at a much lower complexity cost. Furthermore, it turns out that these results can be explained in terms of the "overtaking" effect, i.e. bursts arriving earlier than other bursts despite the Burst Control Packet (BCP) has actually arrived after the BCP of the overtaken bursts.**

***Index Terms*— OBS, scheduling algorithm, burst size, offset variability, overtaking probability**

I. Introduction

Several switching approaches are currently being considered for all-optical networks: optical circuit switching (OCS), optical packet switching (OPS) and optical burst switching (OBS). The main drawback of OCS is the circuit setup time, which can take more than the circuit holding time. On the other hand, no setup time is incurred with OPS, but the packet header has to be interpreted in the electrical domain on a hop-by-hop basis, which is very challenging for Gbps speeds. The OBS approach is actually a combination of both OCS and OPS. A Burst Control Packet (BCP) is sent an offset time before the optical burst transmission. Thus, the BCP announces the optical burst arrival to the intermediate OBS switches, which reserve a wavelength in the corresponding output port. Typically, the BCP contains information about the arrival instant of the incoming burst, and also about the burst size. Consequently, the output wavelength is reserved only for the burst transmission time, possibly adding a guard band. This approach is called Just Enough Time (JET) [1], and it will be assumed in what follows.

Note that the optical burst is transmitted without confirmation. Thus, chances are that the output wavelength cannot be reserved in an intermediate switch. As a result, the burst will be dropped. A number of burst scheduling algorithms have been proposed to minimise the burst dropping probability. Assuming wavelength conversion capabilities are available at the switch, there are a number of wavelengths to choose from. Precisely, the scheduling algorithms differ in the way the wavelength selection is performed. The simplest approach is to choose the first available wavelength. Note that this approach leads to a very high utilization of the wavelengths that are probed first. An alternate approach is to consider the smallest void (in duration) among the ones the optical burst fits in. It becomes apparent that the latter reduces fragmentation, albeit this is at the expense of a higher computational cost.

In evaluating the scheduling algorithms, two fundamental issues have to be considered. First, the burst size is a random variable. In fact, bursts are generated at the network edges by a functional unit that will be denoted by "burstifier". Time-based and size-based algorithms have been considered (or a combination of both), that produce bursts with different burst sizes. Clearly, a size-based burstification algorithm will produce bursts with the same size, but a time-based algorithm will not. A number of size distributions have been considered for that case, including Gaussian and Gamma distributions [2], [3].

Secondly, the offset time is also a random variable. This is a consequence of the different distances of the burstifiers to a given switch, in number of hops. At each intermediate switch there is a BCP processing time which actually decreases the offset time between BCP and burst. Note that the burst does not leave the optical domain, while the BCP is O/E/O converted and processed in the electronic domain. Even if the offset times were the same for all burst in the source burstifiers, the different distances from them to a given switch imply that the offset times will not be the same. Most interestingly, a BCP may announce the arrival of a burst that happens before the arrival of other bursts whose BCPs have already arrived. We call this phenomenon "overtaking".

The burst scheduling algorithm is a central issue in an OBS switch architecture. Therefore, a number of proposals have appeared in the literature [4], [5], [6], [7], [8], [9], [10], [11]. The performance evaluation of the proposed algorithms is focused on the computational complexity and the burst loss ratio, in comparison to other algorithms. However, to the best of our knowledge, no comparative performance evaluation has been published that takes into account the fact that both burst sizes and offset times are non-deterministic.

Actually, by considering the effect of non-deterministic burst sizes and offset times a number of most interesting issues arise. On one hand, the burst size distribution does not affect much the scheduling algorithm performance. This means the burstification algorithm has little influence in the switch blocking probability, no matter the scheduling algorithm being used. While it is well known that the burst size distribution does not affect the switch occupancy distribution, as given by the Erlang-B formula, the results presented in this paper actually extend this invariant property to the scheduling algorithm. On the other hand, the offset time has some influence in the scheduling performance. This fact paves the way for offset compensation algorithms that tend to equalize the offset times at a given switch, with knowledge of the network topology.

Finally, we also evaluate the scheduling algorithms under realistic traffic load and blocking probability. We note that the advent of multimedia services call for more stringent QoS requirements, and optical networks are expected to provide low loss probability. If we examine the scheduling algorithms in a loss probability range below 10^{-5} then the performance of the different scheduling algorithms is very much alike. However, the computational cost radically differs from one algorithm to another. Thus, the choice of a scheduling algorithm is conditioned by the switch loss probability regime. Most interestingly, it turns out that an apparently worse algorithm performs better, if we take into account the computational cost.

In this paper, considerable insight is provided on the practical applicability of well-known scheduling algorithms, through extensive simulation experiments. The paper is structured as follows: In section II we describe the scheduling algorithms under analysis, together with the simulation platform. Section III and section IV are devoted to the influence of burst size and offset time distribution in the scheduling algorithm performance respectively. In section V we present the discussion, and relate the results to the "overtaking" probability. Finally, section VI presents the conclusions that can be drawn from this analysis.

II. Burst Scheduling Algorithms and Simulation Tool

In this paper, we consider the following scheduling algorithms, which are briefly described. Please refer to the references for further information.

1) *First-Fit [8]:* The wavelengths are numbered in increasing order and they are probed sequentially, searching for an available void.
2) *LAUC-VF [8]:*: This algorithm searches for a void in the *Latest Available Unscheduled Channel*. Namely, the algorithm searches for a void whose starting time is as close as possible to the ending time of the previously transmitted burst in the same channel.
3) *Best-Fit [11]*: The algorithm searches for a void with minimum fragmentation. Namely, the algorithms selects the void that generates the shortest voids (in duration) before and after the scheduled burst.
4) *Iizuka algorithm [4]:* It is a variant of LAUC-VF that gives preference to selecting voids between scheduled bursts with respect to placing bursts at the reservation horizon, i. e. with no bursts scheduled for transmission after the incoming burst.

We note that all the algorithms considered in this study perform void filling. The algorithms have been coded in an ad-hoc simulator written in C, which was extensively validated. We used an ad-hoc simulator to be able to evaluate the algorithms performance even in low loss probability regimes. To obtain a robust estimation of the blocking probability for low probability values one needs a very large number of samples, which in turn makes simulation time increase significantly. Therefore, our simulation code is optimized for performance and reasonable simulation times were achieved. The BCP arrival process is assumed to be Poisson [12] and the burst size distribution is assumed to be Gaussian, deterministic or Exponential. The coefficient of variation $c_v^2 = (\text{variance}/\text{mean})^2$ for the Gaussian distribution is always equal to 0.01. As for the offset times, we consider a uniform distribution with different lower and upper bound to analyze the influence of variability on the offset time. We also consider the NSFNet network and derive empirically the offset time distribution, in order to evaluate a realistic case. On the other hand, we will assume that the OBS switches are not equipped with Fiber Delay Lines (FDLs).

In what follows all time units are normalized to the burst transmission time. Unless otherwise stated, in all our figures the x-axis represents the BCP (or burst) arrival rate and the number of wavelengths is equal to 10, even though the same conclusions are obtained with different number of wavelengths. Table I provides a key to the legends in the figures.

Algorithm	Key
First-Fit	fi rstF
LAUC-VF	laucVF
Best-Fit	bestF
Iizuka	Iizuka

TABLE I

KEY TO THE LEGEND IN THE FIGURES

Finally, we also provide the blocking probability results for the Erlang-B formula, for comparison purposes.

III. INFLUENCE OF BURST SIZE DISTRIBUTIONS

Figures 1, 2 and 3 show the burst loss for different scheduling algorithms using Gaussian, deterministic and exponential distributions for the burst size, all with the same average burst size, which is equal to five. The offset time is a uniform random variable in the range $[0, 30]$. In figures 4, 5 and 6 the average burst size is now equal to 15.

It can be seen that in both cases the results are similar if the average burst size is the same, although the burst size distributions are different. Note also that LAUC-VF, Best-Fit or Iizuka algorithms are less sensitive to burst size distribution than First-Fit.

Finally, it is worth noting that if the offset time is constant then all the algorithms perform exactly the same, since there is no void-filling at all. The results for constant offset time will be reported in the next section.

IV. INFLUENCE OF THE OFFSET SIZE DISTRIBUTIONS

Figures 7, 8, 9 and 10 show the burst loss probability for uniform offset distributions with ranges $[0, 10], [0, 30], [0, 100]$ and $[0, 300]$ and Gaussian burst lengths. The average burst size is now constant and equal to 5. The influence of the offset time distribution in the burst loss probability is now striking. Actually, as the offset time variability increases the burst loss probability also increases. This increment is high in the first range

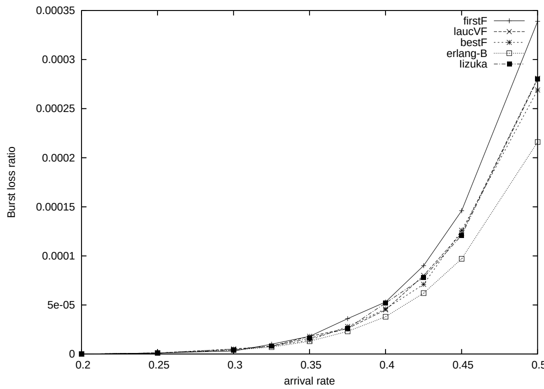

Fig. 1. Offset: Uniformly distributed $[0, 30]$, Gaussian burst length mean=5.0

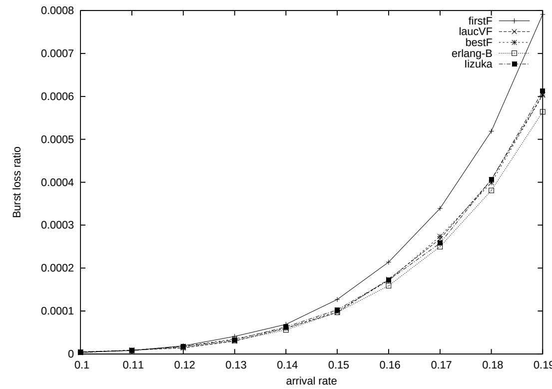

Fig. 4. Offset: Uniformly distributed $[0, 30]$, Gaussian burst length mean=15.0

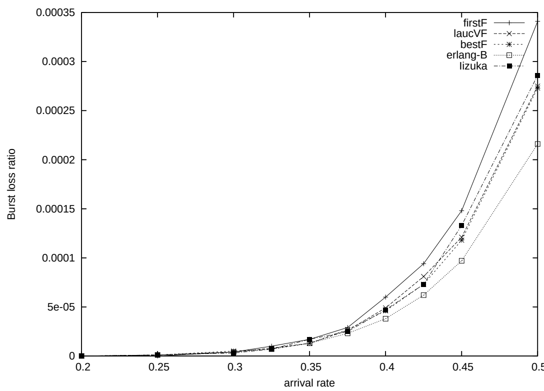

Fig. 2. Offset: Uniformly distributed $[0, 30]$, Deterministic burst length=5.0

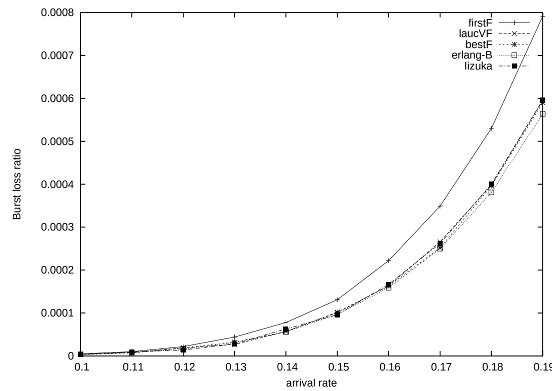

Fig. 5. Offset: Uniformly distributed $[0, 30]$, Deterministic burst length = 15.0

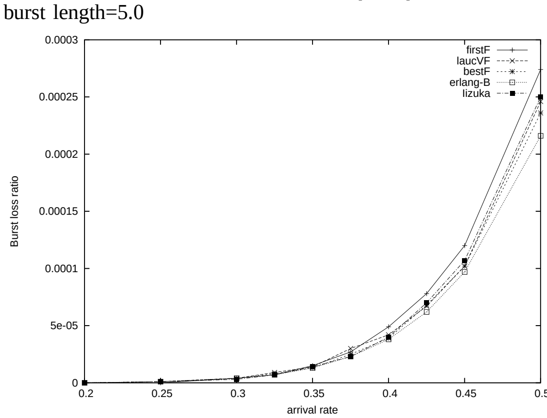

Fig. 3. Offset: Uniformly distributed $[0, 30]$, Exponential burst length mean=5.0

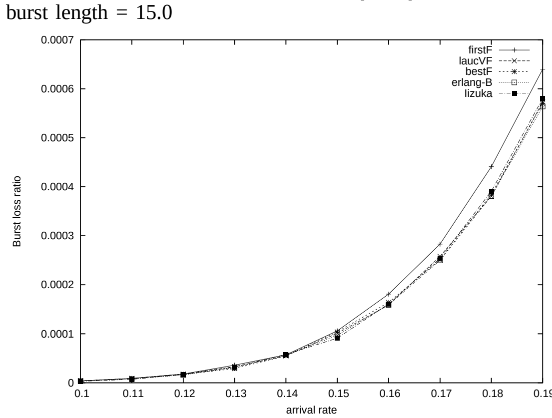

Fig. 6. Offset: Uniformly distributed $[0, 30]$, Exponential burst length mean=15.0

(with respect to Erlang-B), moderate in the second range with respect to the first one, and low in the third and fourth ranges, where the burst loss is nearly the same, and insensitive to the offset variability increment. The reason of this behavior is given in next section, and is directly related to the overtaking probability.

With regard to constant offset times it is interesting to remark that no void-filling occurs because no overtaking happens whatsoever. In that case, the burst dropping probability is determined by the occupancy distribution of the wavelengths. Figure 11 shows the burst dropping probability in that case. All the scheduling algorithms perform exactly the same, and the burst dropping probability is given by the Erlang-B formula [13].

It is also important to point out that the same results are obtained with other burst size distributions (constant, Exponential), not shown here for brevity.

V. Discussion

From our simulation campaign we learnt that the burst dropping probability is influenced by two factors: first, the wavelengths' occupancy and, secondly, an insufficient void size.

Clearly, a burst will be dropped if all the wavelengths are occupied by the moment that burst arrives. Let us denote by P_o the burst dropping probability due to occupancy. Such burst dropping probability is given by the Erlang-B formula. On the other hand, even though there are available wavelengths a burst may be dropped if the burst transmission time is larger than the minimum duration of the available voids. We call this effect *insufficient void size*. Let P_v refer to the burst dropping probability due to insufficient void size. If P is the burst dropping probability then it turns out that $P = P_o + P_v \geq P_o$. Actually, note that the Erlang-B formula is a lower bound for the burst dropping probability in all the performance curves presented in this paper. Furthermore, the fact the P_o is given by the Erlang-B formula is supported by the lemma included in appendix I, that shows that the burst arrival process is Poisson, *no matter that the offset time is variable*.

Nevertheless, as can be seen in figure 11, if the offset time is constant then $P = P_o$. In that case, no overtake between bursts happen. Conversely,

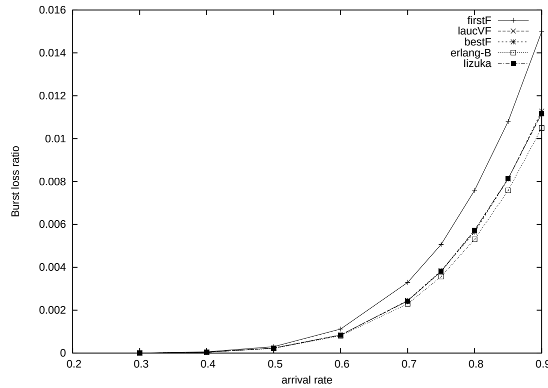

Fig. 7. Offset: Uniformly distributed $[0, 10]$, Gaussian burst length mean=5.0

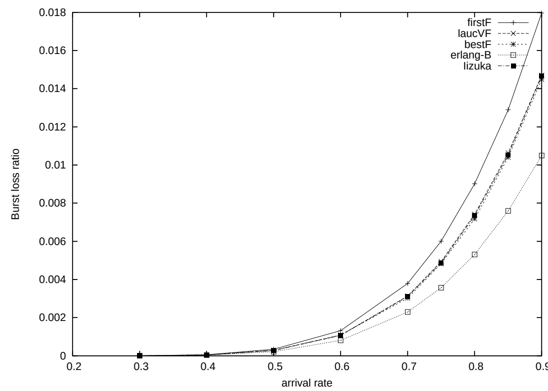

Fig. 8. Offset: Uniformly distributed $[0, 30]$, Gaussian burst length mean=5.0

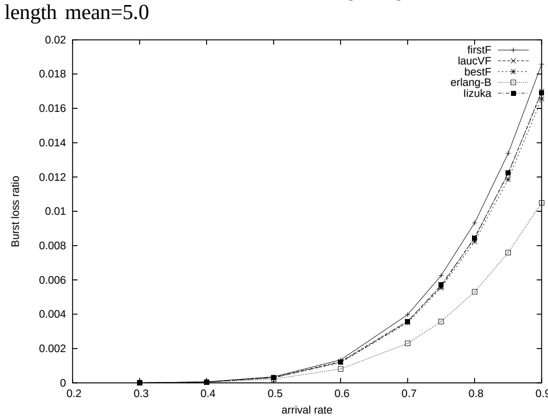

Fig. 9. Offset: Uniformly distributed $[0, 100]$, Gaussian burst length mean=5.0

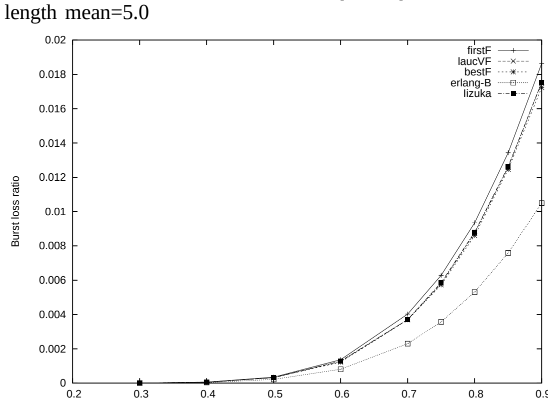

Fig. 10. Offset: Uniformly distributed $[0, 300]$, Gaussian burst length mean=5.0

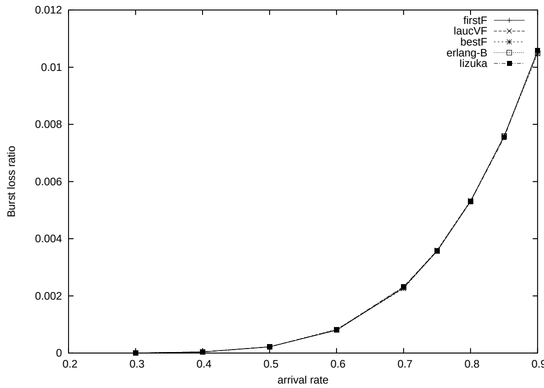

Fig. 11. Offset: Deterministic=3.0, Gaussian burst length mean=15.0

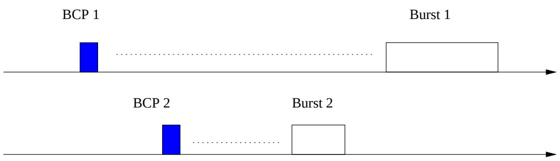

Fig. 12. Burst 2 overtakes burst 1

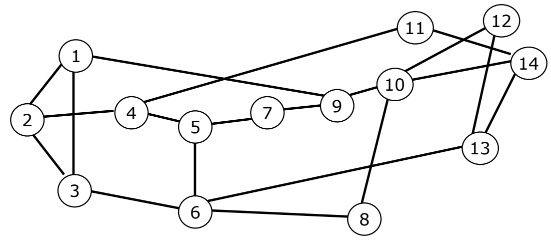

Fig. 13. NSFNet topology

Offset time	Probability
2Δ	0.65137
3Δ	0.33027
4Δ	0.0101834

TABLE II
OFFSET TIME DISTRIBUTION (30,45,60)
P=[0.65137,0.33027,0.01834]

the variable offset time is responsible for the burst overtake, as explained in figure 12.

To evaluate the impact of the burst overtake probability in the burst dropping probability we consider the case of offset times in the NSFNet topology, as seen in figure 13. We calculate all routes from any source to any destination using the minimum number of hops criteria. We assume that that the traffic matrix is homogeneous, i. e., all nodes produce the same traffic to the rest of the nodes. On the other hand, we assume that the BCP processing time at each intermediate switch is equal to Δ. For each of the switches, we obtain the set of upstream switches and derive the offset time distribution. To this end, we consider that the burst offset time at the network edges is equal to 4Δ, i.e. the network diameter in number of hops. Then, for each of the switches upstream from a given switch we subtract Δ to the offset time. The several paths that go across the switch give rise to different offset times at that switch. Namely, the bursts arriving to any given switch in the network have variable offset times. We consider an intermediate switch in the topology and obtain the offset time distribution, by averaging the offset times with the traffic in the paths upstream. The distribution range does not include the value Δ for the offset time as it corresponds to the last hop, which only receives the burst. Namely, it does not relay the burst to the next hop. Thus, the burst is not scheduled in an output wavelength, which is the case under analysis. Table II shows the offset time distribution that was used in our simulation experiment.

Figures 14 and 15 show the burst dropping probability and the overtake probability for the offset time distribution shown in table II, with $\Delta = 15$. We note that roughly 65% of the bursts have the smallest offset time of 2Δ, namely. Then, the overtake probability is relatively high.

Let us now consider, for the sake of comparison, an inverted offset time distribution, namely let us consider the offset time distribution $(30, 45, 60)$ with probability vector $p = [0.01834, 0.33027, 0.65137]$. We choose this distribution because the shortest offset time 30 is now less frequent (roughly 2%). Figures 16 and 17 show the burst dropping probability and the overtake probability for the new offset time distribution. Since the overtake probability now decreases, it turns out that the burst dropping probability also decreases as expected. In this case, there are less chances of void filling, and the burst dropping probability due to insufficient void size now decreases.

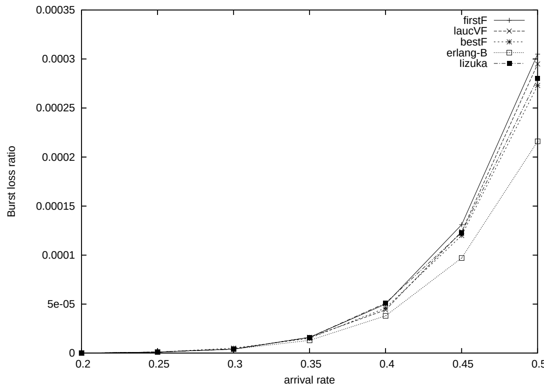

Fig. 14. Burst dropping probability Offset: Discrete (30, 45, 60) p=[0.65137,0.33027,0.01834], Gaussian burst length mean=5

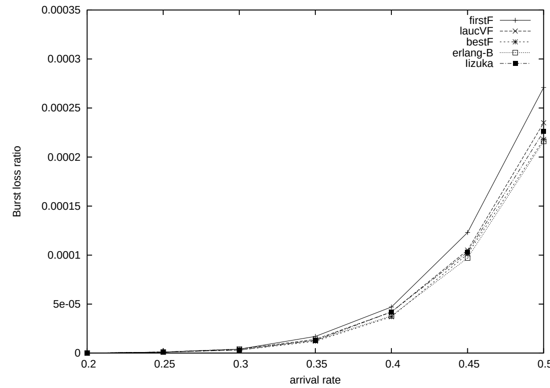

Fig. 16. Burst dropping probability Offset: Discrete (30, 45, 60) p=[0.01834,0.33027,0.65137], Gaussian burst length mean=5.0

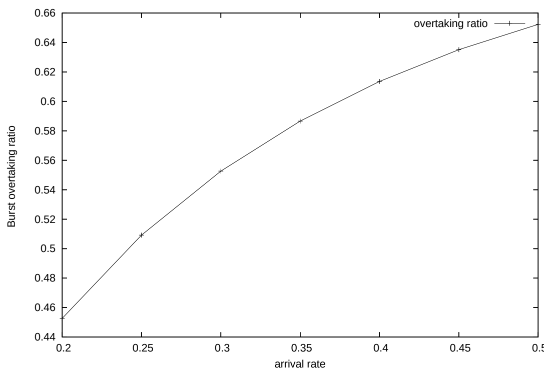

Fig. 15. Overtake probability Offset: Discrete (30,45,60) p=[0.65137,0.33027,0.01834], Gaussian burst length mean=5

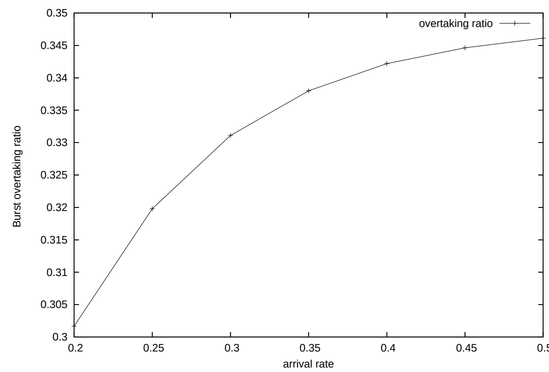

Fig. 17. Overtake probability Offset: Discrete [0.01834,0.33027,0.65137], Gaussian burst length mean=5.0

This fact explains the behavior identified in section IV when analyzing figures 7-10: if the offset varies in the range $[0, 10]$, the overtaking probability increases rapidly from zero and the performance gets worse. Then, in the range $[0, 30]$, the overtaking probability and the burst loss increase again notably. Next, in the range $[0, 100]$ the overtaking probability increases again, but not so much. Finally, in the range $[0, 300]$ the overtaking probability and the burst loss tend to stabilize. Logically, when the overtaking probability is near 100% the rate of increase cannot be that large, thus reducing the sensitiveness to offset variations. It is also interesting to note that First-Fit algorithm is more sensitive to such overtaking probability, being the rest of algorithms more adaptive to this variability, needing a higher variability to achieve the stable burst loss.

It is worth remarking that there are scheduling algorithms, which are not considered in this paper, that tackle the overtake issue using ordered scheduling [6], or bursts rescheduling [7]. As an alternate approach, the Virtual Fixed Offset scheduling algorithm [5] reduces the variability of the offset times. However, the main drawback of these algorithms is the extra signalling which is required to reallocate bursts and the increased computational effort.

A. Low loss rate regime

Optical networks are expected to provide low packet dropping probability. This motivates the analysis of the scheduling algorithms under low loss rate regime. Furthermore, considering sparse network topologies and a loss probability vector $(p_1, \ldots, p_M)$ for a path traversing switches

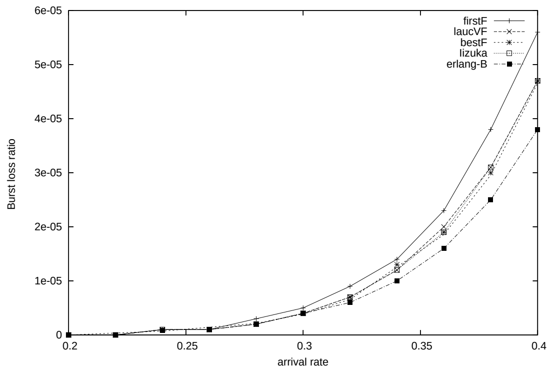

Fig. 18. Burst dropping probability Offset: Uniformly distributed $[0, 30]$, Gaussian burst length mean=5.0

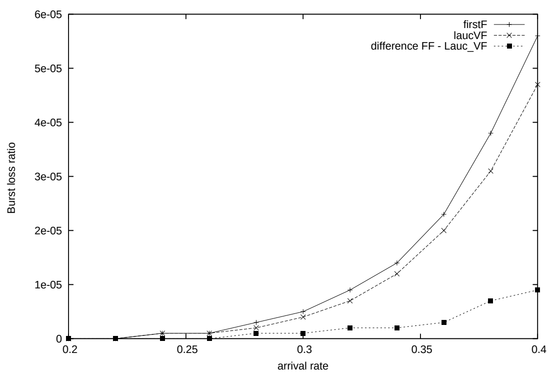

Fig. 19. Comparison between LAUC-VF and First-Fit algorithms

$1, \ldots, M$ then it turns out that the path burst dropping probability p can be approximated as $p \approx \sum_{i=1}^{M} p_i$, if the p_is are small. This further motivates the investigation of scheduling algorithms in low loss rate regime, because the loss probability is additive, the worse the larger the path in number of hops. Thus, the loss probability at each individual switch must be kept reasonably small.

Figure 18 shows the burst dropping probability of the different scheduling algorithms, for dropping probabilities smaller than 10^{-4}. While LAUC-VF provides the best performance, the difference is bounded by $3 \cdot 10^{-5}$. This is actually shown in figure 19, which shows the difference between the worst and the best scheduling algorithms in figure 18. However, we note that the difference in computational cost is very significant, as will be explained in the next subsection.

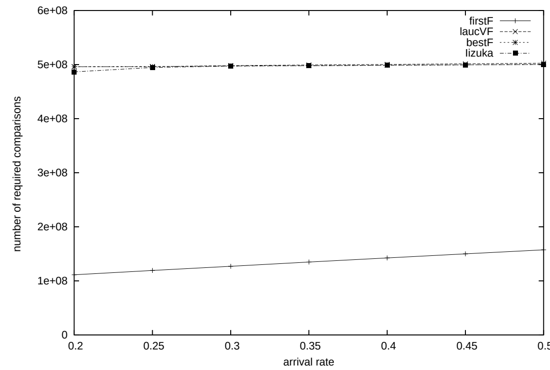

Fig. 20. Offset: Uniformly distributed $[0, 3]$, Gaussian burst length mean=5.0

B. Computation cost

The computational cost of a scheduling algorithm relates to the BCP service time, which is in turn related to the offset time. If the execution time of a scheduling algorithm is large, then the offset time must also be large. Otherwise, chances are that the burst reaches a given switch *before* the associated BCP, because it was delayed too much in the upstream switches. Furthermore, large execution times are also a limiting factor for switch scalability, since the same control unit will not be able to serve an increasing number of wavelengths, and will have to be replaced. It is expected that the number of wavelengths increases, as the underlying optical technological becomes more mature.

To evaluate the computational cost, we consider that probing a wavelength for a void is a basic task in the scheduling algorithm. Figure 20 shows the number of tasks (i.e. checking whether there is a void in a wavelength or not for the incoming burst) for $15, 000, 000$ bursts processed. The offset is uniform in the range $[0, 30]$ and the burst length is Gaussian.

Clearly, the First-Fit algorithm shows a much lower computational cost, since it does not require checking every wavelength in order to find the shortest void, as happens with Best-Fit or LAUC-VF. At low loss rate regimes, one has to trade-off the simplicity of the scheduling algorithm implementation versus the real gains in terms of burst dropping probability, as indicated by figures 18 and 19.

C. Validation

Finally, it is worth mentioning that our simulation campaign also serves to validate previously published results, concerning QoS differentiation with offset time. Figure 21 shows the offset time Cumulative Distribution Function (CDF) for dropped bursts, with uniform offset times and burst lengths. It turns out that bursts with smaller offset times have more chances to be dropped than bursts with larger offset times, as it is commonly accepted [8]. On the other hand, figure 22 shows the burst size CDF for dropped bursts, which shows that larger bursts have a larger dropping probability. This matches our intuition that it is harder to find a void for large burst than for small bursts. However, this is not in contradiction with the fact that the burst size distribution does not affect the burst dropping probability (see section III). It only shows that *within the same burst size distribution*, large bursts are more likely to be dropped.

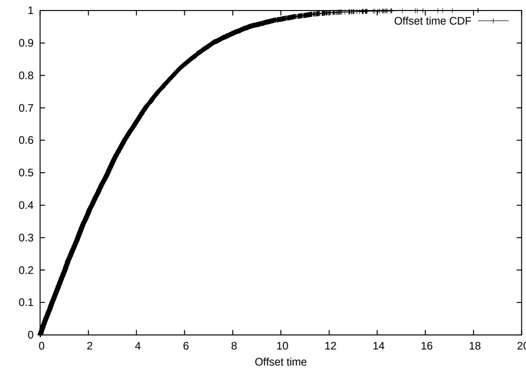

Fig. 21. Offset time CDF (dropped bursts), Offset: Uniformly distributed $[0, 30]$, Uniform burst length $[0, 10]$

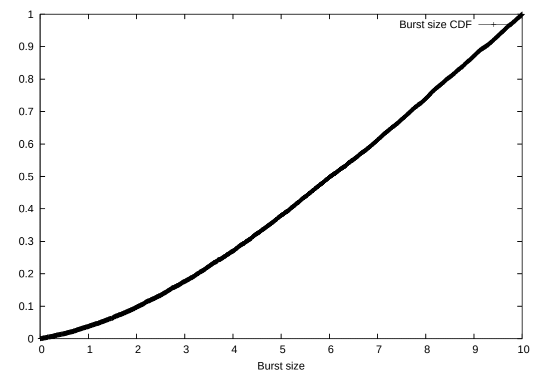

Fig. 22. Burst size CDF (dropped bursts), Offset: Uniformly distributed $[0, 30]$, Uniform burst length $[0, 10]$

VI. Conclusions and Future Work

The results presented in this paper provide considerable insight into the dynamics and performance of burst scheduling algorithms. First, our findings show that the burst size distribution does not affect the burst dropping probability significantly, but the same does not apply to offset times. On the other hand, we decompose the dropping probability in two terms: the first due to occupancy and the second due to insufficient void size. We show that the latter is affected by the overtake probability, the larger the overtake probability the worse the performance.

Overall, LAUC-VF shows a better performance in comparison to the rest of the algorithms. Other experiments, not included here for brevity, have shown that Best-Fit and Iizuka algorithms improve their results with respect to LAUC-VF when there is a higher variability on the offset time. However, at realistic low loss rate regimes, the benefits may not pay off for the increased computational cost.

Finally, our findings constitute a departure point for a number of research avenues to pursue. The fact that the scheduling performance is marginally affected by the burst size distribution has an impact in the design of burstification algorithms. On the other hand, we plan to study policies for equalizing the offset time distribution, as the offset time distribution has an influence on burst dropping performance.

Appendix I
Burst Poisson Arrival

Lemma: If BCP arrivals follow a Poisson distribution then burst arrivals follow a Poisson distribution.

Proof:. Let the BCP arrival process be Poisson with rate λ and let $X \sim U(0, Z)$ be the offset time, uniform in the range $[0, Z]$. Let $P_B(t_0, t_0 + \Delta t) = P(1 \text{ burst arrival in}(t_0, t_0 + \Delta t))$ and $P_{\text{BCP}}(t_0, t_0 + \Delta t) = P(1 \text{ BCP arrival in}(t_0, t_0 + \Delta t))$. Then,

$$P_B(t_0, t_0 + \Delta t) = \quad (1)$$
$$\int_0^Z P_{\text{BCP}}(t_0 - x - \Delta t, t_0 - x) | X = x) \frac{1}{Z} dx =$$
$$\int_0^Z (\lambda \Delta t + o(\Delta t)) \frac{1}{Z} dx =$$
$$\lambda \Delta t + o(\Delta t).$$

and the burst arrival process is Poisson with rate λ.

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