Analysis of blocking probability of data bursts with continuous-time variable offsets in single-wavelength OBS switches

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***Abstract*— To reduce contention in Optical Burst Switched networks, data bursts are preceded by the so-called Burst Control Packets, which are sent a given offset time in advance in order to advertise of the forthcoming burst arrivals. However, this policy of one-way in-advanced reservation produces the so-called Path Length Priority Effect, which benefits BCP reservations with high offset values against those with smaller offset times. This effect not only brings an unfair treatment to bursts with different offset values, but also leads to a serious degradation of global network performance.**

This work presents a new detailed analytical study to quantify the blocking probability perceived by BCP reservations with continuous-time uniformly-distributed offset-time values. In addition, it shows how to apply such theoretical values onto a proactive discarding algorithm which reduces such unfairness and achieves an equalised picture of the blocking probability with respect to the offset-time.

I. Introduction and previous work

Recently, Optical Burst Switching (or just OBS) has been proposed by the research community as a possible solution for carrying IP traffic over Dense Wavelength Division Multiplexing (DWDM), which could be deployed in the near future [1], [2]. Among its many benefits, OBS achieves a high utilisation of the huge amount of raw bandwidth available by fibre optics at a moderate complexity cost.

In OBS, data packets travel through the optical infrastructure as part of a longer-size transmission unit, the so-called optical burst, which is entirely switched in the optical domain. Such optical bursts do not suffer from O/E/O conversion at intermediate nodes, thus they experience only propagation delay in the absence of optical buffering devices.

Indeed, since optical buffering devices are, at present, hardly feasible to deploy, burst contention often leads to data loss. That is, when a data burst needs to be transmitted through an already occupied output port, it generally has to be dropped. To prevent, or at least reduce this situation, several scheduling protocols have been proposed in the literature, see Just-In-Time [3], [4], Horizon [5] and Just-Enough-Time [6], and [7], [8], [9] for a comparison of them.

The most widely accepted one, Just-Enough-Time (or JET), employs one-way reservation of resources prior to sending any data. Essentially, every data burst is preceded by the so-called Burst-Control Packet (or BCP), which is sent ahead on attempts to reserve resources at every node along the source-to-destination path. Typically, the BCP contains the expected arrival time at the core nodes and the size of its associated data burst, which is used in the process of burst scheduling at core nodes.

The amount of time the BCP is sent in advanced, i.e. the *offset time*, must be carefully designed to provide enough time for its O/E conversion and processing at each intermediate node. Essentially, such processing consists of searching for an available unscheduled gap at which to allocate the forthcoming data burst [10]. Clearly, the offset time value must be larger than the total amount of burst scheduling time in the entire path, otherwise the data burst would overtake its associated BCP.

However, in a real network scenario where offset values are variable, the performance operation of the OBS network and the Quality of Service perceived by the end users present the following drawbacks: On the one hand, variable offset times produce the so-called *retroblocking effect*, at which early BCP reservations may cause blocking to one or many successive attempts for burst scheduling on the same wavelength starting earlier than the already reserved time-slot [11]. On the other hand, BCP arrivals with small offset time values have been shown to encounter serious difficulties in finding available time-slots since they have to compete with much earlier BCP reservations.

The latter effect might be exploited to differentiate between classes of traffic, where high priority traffic is given extra offset time to reduce its blocking probality at core nodes [12], [13]. However, this mechanism presents a few drawbacks, mainly the extra delay experienced by the high-priority packets, which might not be tolerated by some particular applications.

Nevertheless, as the BCP packet traverses the network, its offset time value is reduced and thus, the probability of successfully finding an available time slot decreases [14]. This effect is often referred to as the *Path Length Priority Effect* (PLPE) [15] or *Beat-Down Unfairness Problem* [16] in the literature. Regardless of the unfairness treatment to packets of the same QoS class, PLPE is also very harmful from the point of view of global network efficiency, for one simple reason: Those bursts closer to their destination are more likely to be dropped since their offset-time has been reduced while traversing the network. This degrades the end-to-end throughput very significantly.

A number of solutions have been proposed to overcome PLPE, i.e. to bring fainess to OBS: In [15], the authors propose Hop-by-hop Priority Increasing (HPI), a mechanism to provide extra offset time at intermediate nodes via Fiber Delay Lines (FDLs) to compensate for the offset time lost in the processing of BCPs at every host. However, this scheme requires all core nodes to implement HPI, otherwise the fairness in the other nodes may be affected, and also it increases the delay experienced by bursts. In [17], the authors propose a backward reservation algorithm at which the destination node addresses the reservation process, which brakes with the JET philosophy. Also, it has been proposed in [18] a "merit-based" mechanism at which incoming data bursts are ranked according to some merit metric. Such metric takes into consideration key performance aspects such as destination proximity to benefit data bursts which have already consumed substantial network resources. Also, fairness can be improved by reducing the search space for free wavelength at core switches (see [16] for further details).

Finally, proactive mechanisms constitute the majority of studies due to their simplicity. Essentially, proactive mechanisms causes deliberate burst drops to those packets which are typically benefited by PLPE. The difference between the algorithms proposed lies in the mechanism to adjust such deliberate discarding probabilities. The *Proactive Random Early Dropping* (PRED) proposed in [16] only states that such discarding probabilities must decrease with the proximity of the burst to its destination. The authors in [19] propose a monitor-based algorithm to estimate the probabilities and adjust the subsequent deliberated dropping probabilities based on measurements.

Nevertheless, in order to propose efficient algorithms to remove PLPE, it is first necessary to accurately characterise such phenomena. In this light, from an analytical point of view, only a few studies have attempted to model the differences in terms of blocking probability observed by BCP arrivals with variable offset-time values. On the one hand, Barakat et. al. [13], [20] derive an expression for the distribution of the number of bursts that contend with a given arriving burst. However, this work assumes that the offset-time values are constant for data bursts of the same QoS class, but different when compared to other classes, hence do not consider the case for continuous-time variable offset times. On the other hand, the model proposed in [21] considers uniformly-distributed offset times, but the methodology used (two-state non-homogenous Markov chain) only provides the blocking probability conditioned to a particular value of burst size and offset-time value. Additionally, the latter assumes that the channel is slotted.

In conclusion, to the best of the authors' knowledge, no accurate analytical expression has been derived to characterise and quantify the blocking probability experienced by data bursts with continuous offset time values, which causes unfair switching behaviour. Finding an analytical expression of such variable blocking probability would clearly benefit in the design and adjustment of such deliberate discarding probabilities defined by the proactive mechanisms to reduce PLPE.

The main contribution of this work is two-fold: First, it aims to provide an accurate approximation to the blocking probability experienced by data bursts with continuous-time variable offset values on a single-wavelength optical switch (or multiple-wavelength switch but without wavelength conversion capabality). Secondly, it shows how to apply such analysis in the design of an offset priority equaliser for core OBS nodes, on attempts to reduce PLPE. To this end, the remainder of this work is organised as follows: Section II shows how to derive the blocking probability experienced by BCPs with uniformly-distributed offset values following a fixed-point approximation method and how to apply this result to derive the blocking probability observed by bursts with different offset-time values. Then, section III validates the equations derived in the previous section via simulation. After this, section IV shows how to apply the equations derived in the analysis to design a proactive mechanism to equalise the blocking probability for continuous-time variable offset-time values. Finally, section V summarises the main findings presented in this work and provides further lines of investigation and application of this study.

II. Analysis

A. Preliminaries

The blocking probability is derived as the probability to find no available gaps at which to allocate a data burst observed by a given randomly chosen BCP (the tagged BCP in what follows). Let the tagged BCP be assumed to arrive at time $t = 0$ at the scheduler of the OBS node, and let its offset time be uniformly distributed (see figure 1). As shown, the interval time $[0, T]$ denotes the horizon time of the BCP, that is, the time range over which the tagged BCP attempts to reserve its associated data burst. Also, the interval time $[-T, 0]$ is refered to as the *past-horizon time*, that is, T units of time right in the past of the tagged BCP arrival. As shown below, the past-horizon time is key in determining the blocking probability of the tagged BCP, since some arrivals over it may attempt for reservations in the horizon time of the tagged BCP.

The process to determine the blocking probability observed by the tagged BCP requires the following findings: (1) determine the number of attempts for reservation in the horizon time of the tagged BCP; (2) obtain the actual number of successfully scheduled data bursts in the horizon time of the tagged BCP, and (3) derive the probability to fit an extra

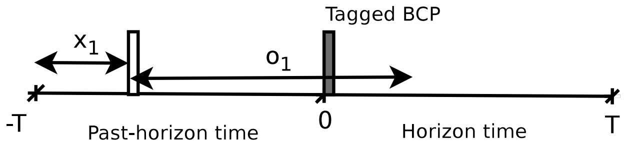

Fig. 1. Notation

data burst in the horizon time assuming a number of already scheduled data bursts. Accordingly, let us define the following events:

- A_n: Number of arrivals in the past-horizon of the tagged BCP.
- B_m: Number of attempts for scheduling in the horizon of the tagged BCP.
- R_j: Number of successfully scheduled data bursts in the horizon of the tagged BCP.

In what follows, the authors assume that BCPs arrive at the scheduler of a given core OBS node following a Poissonian basis with average incoming rate λ. This assumption is typically considered in the performance evaluation studies of high-speed operational backbones, particularly those at which the OBS paradigm has a potential application [22], [23], [24], [25], [26], [27] and is gaining in importance among the network research community after the recent studies on network traffic measurements carried out by Karagiannis et. al. [28] and Haga et. al. [29]. Thus, the number of arrivals in the past-horizon time of the tagged BCP follows a Poisson distribution with rate λ:

$$P(A_n) = \frac{(\lambda T)^n}{n!} e^{-\lambda T}, \quad n = 0, 1, \dots \tag{1}$$

Hence, the BCP interarrival times are negative exponentially distributed with mean $1/\lambda$.

Let n denote the number of arrivals that actually occur in the past-horizon time of the tagged BCP, and let x_i, $i = 1, \dots, n$ denote the arrival time of the i-th BCP arrival, and let o_i, $i = 1, \dots, n$ refer to its associated offset time (fig. 1). It is well known that, given n Poisson arrivals within time $[-T, 0]$, such n arrivals are independently and uniformly distributed in the interval, that is, $x_i \sim U(-T, 0)$.

Also, the offset-time values that is, the difference between the BCP arrival and its associated data burst arrival shall be assumed uniformly distributed with maximum value T, i.e. $U(0, T)$. Such assumption arises from the fact that a given core OBS node typically receives BCP reservations with disparate destinations, some of them are far (large offset values) but some others are close (small offset values). The assumption of offset values uniformly distributed between $[0, T]$ aims to cover most typical scenarios. Thus, $o_i \sim U(0, T)$.

B. Analysis of the process B_m

This section aims to derive the probability distribution of the event B_m defined above, that is, the number of attempts for reservation in the horizon time of the tagged BCP. Clearly, only BCP arrivals within time $[-T, 0]$ (the past-horizon) may attempt for a reservation for their associated data bursts at any time in the interval $[0, T]$, since the offset-time distribution is $U(0, T)$ (see fig. 1). Obviously, packets arriving at time $t < -T$ do not count since they could never possibly schedule their associated bursts within time $t \in [0, T]$, and so applies to BCP arrivals after $t > 0$ for the tagged BCP would have preference over them since it arrived earlier. Thus, the number of attempts for reservation in the horizon time of the tagged BCP constitutes only a portion of the arrivals in its past-horizon time.

For simplicity, let $A_n = 1$ (one arrival in the past-horizon time of the tagged BCP). The probability to have one attempts for reservation in the horizon time of the tagged BCP $P(B_1|A_1)$ is equivalent to finding the probability that $x_1 + o_1 > 0$. That is:

$$\begin{aligned} P(B_1|A_1) &= \int_{-T}^{0} Pr(o_1 > -x_1) f_{x_1}(x) dx \\ &= \int_{-T}^{0} \frac{-x}{T} \frac{1}{T} dx = \frac{1}{2} \end{aligned} \tag{2}$$

That is, only one half of the arrivals in the past-horizon time of the tagged BCP attempt for reservation over the horizon time, while the other half attempt for reservation over the past-horizon time of the tagged BCP.

Since the n BCP arrivals are independent and have the same probability to attempt for a reservation over $[0, T]$ (i.e. $P(B_1|A_1) = \frac{1}{2}$), the probability $P(B_m|A_n)$ is given by the following binomial distribution:

$$P(B_m|A_n) = \binom{n}{m} \left(\frac{1}{2}\right)^m \left(1 - \frac{1}{2}\right)^{n-m} \tag{3}$$

with $n \leq m$. Thus, since the n BCPs arrive following a Poissonian basis with rate λ, the number m of attempts for scheduling over $[0, T]$ is given by:

$$\begin{aligned} P(B_m) &= \sum_{n=m}^{\infty} \binom{n}{m} \left(\frac{1}{2}\right)^m \left(1 - \frac{1}{2}\right)^{n-m} \frac{(\lambda T)^n}{n!} e^{-\lambda T} \\ &= \frac{(\frac{\lambda T}{2})^m}{m!} e^{-\lambda T} \sum_{n=m}^{\infty} \frac{(\frac{\lambda T}{2})^{n-m}}{(n-m)!} \\ &= \frac{(\frac{\lambda}{2} T)^m}{m!} e^{-\frac{\lambda}{2} T} \end{aligned} \tag{4}$$

which is again a Poisson process but with rate $\frac{\lambda}{2}$, as shown.

Finally, it is also important to derive the number of reservations over a time interval different than $[0, T]$. For instance, let us chunk the interval $[0, T]$ into k_{max} portions of size $T_p = \frac{T}{k_{\text{max}}}$. In this case, it can be easily seen that only those BCP arrivals within the range $[kT_p - T, 0]$ (only part of the past-horizon time) may attempt for a reservation over the range of interest $[kT_p, (k+1)T_p]$, $k = 0, 1, \dots, k_{\text{max}} - 1$ (see Fig. 2). This occurs with probability:

$$
\begin{aligned}
p_k &= \int_{kT_p-T}^{0} Pr(kT_p - x_1 \le o_1 \le (k+1)T_p - x_1) \\
& f_{x_1}(x)dx = \\
&= \int_{kT_p-T}^{0} \frac{T_p}{T}\frac{1}{T}dx = \frac{T_p}{T} - k\left(\frac{T_p}{T}\right)^2 \qquad (5)
\end{aligned}
$$

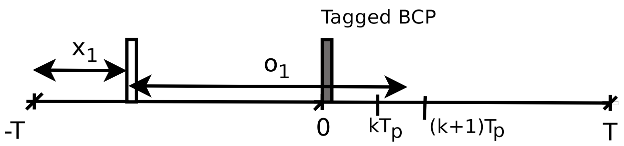

Fig. 2. Number of arrivals within $[kT_p, (k+1)T_p]$

Thus, with this new value p_k, it is easy to demonstrate that the number of reservation attempts in the range $[kT_p, (k+1)T_p]$ follows a Poisson distribution with rate λp_k, i.e.:

$$
P(B_m^{(kT_p,(k+1)T_p)}) = \frac{(\lambda p_k T)^m}{m!} e^{-\lambda p_k T}, \quad k = 0, \ldots, k_{\text{max}} \qquad (6)
$$

C. Probability of successful reservation of the tagged burst

This section studies the probability to find a gap in the horizon time of the tagged BCP, that is $[0, T]$, over which to allocate its associated data burst. To do so, let j refer to the number of reservation attempts within the horizon time of the "tagged" BCP, and let $(Y_1, \ldots, Y_j)$ be the j-dimensional random variable which denotes the *sorted* arrival times of such bursts. Following [30], the joint-probability distribution of $(Y_1, \ldots, Y_j)$ is given by:

$$
f_{Y_1,\ldots,Y_j}(y_1, \ldots, y_j) = \frac{j!}{T^j} \qquad (7)
$$

which gives the joint-probability density function of the order statistics of j uniformly distributed arrivals within time $[0, T]$.

Also, let D refer to the *fixed* service time of each burst (equal-size data bursts), and let $P(R_j)$ denote the probability to have j successfully allocated bursts over $[0, T]$. In other words, $P(R_j)$ gives the probability that *none* of the j data bursts overlap with any of the other. It is easy to derive such probability $P(R_j)$, for the case $j = 1$ following eq. 7:

$$
P(R_1) = \int_0^T \frac{1!}{T^1} dy_1 = \frac{T}{T} = 1 \qquad (8)
$$

Obviously, if only one burst arrives within $[0, T]$, it is impossible that it overlaps with any other.

For $j = 2$ (see fig. 3), the two data burst overlap if $y_2 < y_1 + D$ (remember that the y_i, $i = 1 \ldots, j$ values are sorted, $y_1 < y_2$). Hence:

$$
\begin{aligned}
P(R_2) &= \int_0^{y_2-D} dy_1 \int_D^T \frac{2!}{T^2} dy_2 \\
&= \frac{2!}{T^2} \int_D^T (y_2 - D) dy_2 \\
&= \frac{2!}{T^2} \frac{(T-D)^2}{2} = \left(\frac{T-D}{T}\right)^2 \qquad (9)
\end{aligned}
$$

which gives the non-overlaping probability for $j = 2$ reservation attempts.

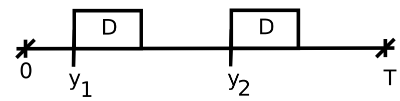

Fig. 3. Case of $j = 2$ arrivals of size D in $[0, T]$

Similarly, for $j = 3$ (fig. 4):

$$
\begin{aligned}
P(R_3) &= \int_0^{y_2-D} dy_1 \int_D^{y_3-D} dy_2 \int_{2D}^T \frac{3!}{T^3} dy_3 \\
&= \frac{3!}{T^3} \int_D^{y_3-D} (y_2 - D) dy_2 \int_{2D}^T dy_3 \\
&= \frac{3!}{T^3} \int_{2D}^T \frac{(y_3 - 2D)^2}{2} dy_3 = \frac{3!}{T^3} \frac{(T-2D)^3}{2 \cdot 3} \\
&= \left(\frac{T-2D}{T}\right)^3 \qquad (10)
\end{aligned}
$$

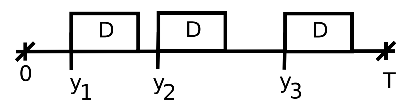

Fig. 4. Case of $j = 3$ arrivals of size D in $[0, T]$

Following this reasoning, it can be shown that, for any number of scheduling attempts j, the non-overlaping probability among any of them is given by:

$$
P(R_j) = \left(\frac{T - (j-1)D}{T}\right)^j \qquad (11)
$$

This equation is key to provide the probability to successfully allocate the tagged data burst assuming that j data bursts have already been successfully allocated:

$$
\begin{aligned}
P(R_{j+1}|R_j) &= \frac{P(R_{j+1})}{P(R_j)} = \frac{\left(\frac{T-jD}{T}\right)^{j+1}}{\left(\frac{T-(j-1)D}{T}\right)^j} \\
&= \frac{1}{T} \frac{(T - jD)^{j+1}}{(T - (j-1)D)^j}, \quad j = 0, 1, \ldots \qquad (12)
\end{aligned}
$$

since R_{j+1} implies R_j and, consequently, $P(R_{j+1} \cap R_j) = P(R_{j+1})$.

D. Blocking probability analysis and fixed-point equation

This section combines all the equations above into a fixed-point equation to obtain the blocking probability observed by the tagged BCP.

The probability to find a gap over which to reserve the data burst associated to the tagged BCP equals the probability to actually fit an extra data burst in its horizon time assuming that a number j of them are already successfully fitted (eq. 12). In this light, the number j of data bursts that are successfully fitted is a portion of the total number of attempts for reservation $m \geq j$ over the horizon time interval, since some of them $(m-j)$ were blocked with probability B. It is also worth remarking that the number $m = 0, 1, \ldots$ of arrivals over the horizon time of the tagged BCP is given by eq. 4. In this light, the blocking probability experienced by the tagged BCP is implicitly stated in:

$$\begin{aligned} 1 - B &= \sum_{m=0}^{\infty} \sum_{j=0}^{m} \binom{m}{j} (1-B)^j B^{m-j} P(R_{j+1}|R_j) \times \\ &\times \frac{(\frac{\lambda}{2}T)^m}{m!} e^{-\frac{\lambda}{2}T} \end{aligned} \tag{13}$$

Essentially, on the left-hand side of the equation, $1 - B$ represents the probability to successfully find a gap for a data burst, as seen by the tagged BCP. On the right-hand side, the equation shows that such probability is equivalent to successfully fitting an extra data burst assuming that j data bursts are already successfully scheduled. The number $j \leq m$ of fitted data bursts is the result of m attempts for reservation, such that $m - j$ out of them were actually blocked with the same blocking probability B as in the left-hand side of the equation.

Clearly, this equation assumes that the blocking probability observed by the tagged BCP is the same as the blocking probability observed by the m attempts for scheduling over the horizon time of the tagged BCP. In other words, the previous equation provides the blocking probability for bursts with offset time in the interval $[0, T]$, i.e. with no restrictions at all in the offset time values. In the next section, we provide an approximation for the case of offset times values being restricted to a given interval.

E. Blocking probability in the range $[kT_p, (k+1)T_p]$

Section II-B has derived the distribution of reservation attempts in the chunk $[kT_p, (k+1)T_p] \in [0, T]$, $k = 0, \ldots, k_{\text{max}}$ of the horizon time. Thus, it is possible to study the blocking probability experienced by the "tagged" BCP assuming its offset time lies within such time interval $[kT_p, (k+1)T_p]$. To do so, it is just necessary to adapt the equations derived above to this case. That is, assuming m arrivals over $[kT_p, (k+1)T_p]$, and $j \leq m$ blocks in it, the blocking probability experienced by the "tagged" BCP can be approximated by:

$$\begin{aligned} 1 - B_k &\approx \sum_{m=0}^{\infty} \sum_{j=0}^{m} \binom{m}{j} (1-B)^j B^{m-j} P_k(R_{j+1}|R_j) \times \\ &\times \frac{(\lambda p_k T)^m}{m!} e^{-\lambda p_k T} \end{aligned} \tag{14}$$

where:

$$P_k(R_{m-j+1}|R_{m-j}) = \frac{1}{T_p} \frac{(T_p - (m-j)D)^{m-j+1}}{(T_p - (m-j-1)D)^{m-j}} \tag{15}$$

and $p_k = \frac{T_p}{T} - k\left(\frac{T_p}{T}\right)^2$, $k = 0, \ldots, \lfloor \frac{T}{T_p} \rfloor$.

This gives the blocking probability of a "tagged" BCP with offset time value uniformly distributed in $[kT_p, (k+1)T_p]$, which has to compete with BCP reservations in the same time interval.

In this case, eq. 14 does not constitute a fixed-point equation since on the right-hand side of the equation, the blocking probability of the m arrivals over the slice $[kT_p, (k+1)T_p]$ is assumed to be B. This is clearly an approximation, since we are taking the blocking probability of bursts with offset times in the interval $[0, T]$ in the right-hand side of the equation. Clearly, not all the BCP arrivals in the post-horizon interval $[-T, 0]$ will eventually produce a burst arrival in the interval $[kT_p, (k+1)T_p]$. However, this approximation is necessary to make the problem analytically tractable. Actually, similar approximations are performed in [13] for realistic network scenarios with small blocking probability. Furthermore, our simulation results assess the validity of such approximation.

III. Experiments

This section aims to check via simulations the equations derived above.

A. On checking the arrival process

As explained above, the probability distribution of a BCP reservation of the arrivals in the range $[-T, 0]$ is the convolution of the two random variables distributed uniformly, $x_i \sim U(-T, 0)$ and $o_i \sim U(0, T)$. Such convolution has the shape of a triangle as shown in fig. 5.

In such figure, a number of 10^6 BCP arrivals within $[-10, 0]$ have been simulated, along with their corresponding offset values. The sum of these two random variables is shown, together with the theoretical values for each of the histogram bins (bin-size: $T_p = 1$) obtained in eq. 5. It can be seen that the theoretical equation accurately matches the simulated results, as expected.

As shown, half of the total events attempt for reservation within the horizon time of the tagged BCP, while the other half target the range $[-T, 0]$. This agrees with the result of Poisson reservations of rate $\lambda/2$ derived in section II-B. Also, it is worth noticing that the number of attempts for reservation in the first histogram bin after $t = 0$ is significantly larger than in the last histogram bin, due to the convolution of the two uniform random variables. For this reason, a "tagged" BCP with a small offset value encounters more difficulties in

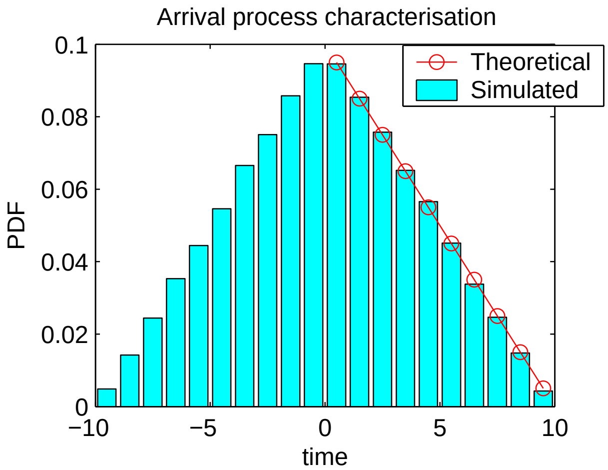

Fig. 5. Simulation of the BCP arrival process with $T = 10$ and $T_p = 1$ (bin-size).

successfully scheduling its associated data bursts than those with larger offset time values, since it has to compete with more reservation attempts.

B. On checking the non-overlapping probability $P(R_j)$

Fig. 6 shows the non-overlaping probability obtained via simulation and theoretical (see eq. 11) of burst arrivals of size $D = 0.15$ in the range $[0, 10]$ (again, $T = 10$). For simplicity, only the range of $j \in [0, 20]$ arrivals have been considered out of the maximum $j_{\text{max}} = \lfloor \frac{T}{D} \rfloor = 66$.

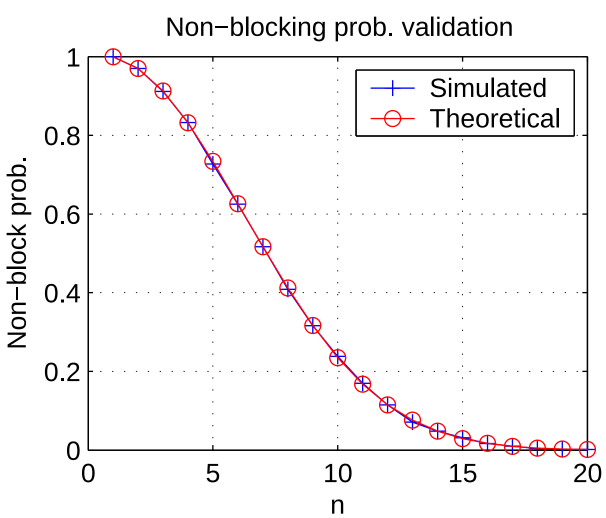

Fig. 6. Non-blocking probability assuming several burst arrivals of size $D = 0.15$ within time $[0, 10]$ (T_{10}).

As shown, the theoretical values perfectly match the simulated results, as expected. It is also worth noticing that such non-overlaping probability decays very fast as j grows.

C. Fixed-point approximation equation and comparison with the Erlang-B formula

This section aims to show the validity of the fixed-point approximation derived in eq. 13 obtained in section II-D. To this end, a simulation of 10^7 events (BCP arrivals) was run, with system parameters: $T = 10$, $D = 0.15$ and several load values $\rho = \lambda D$. The results obtained are depicted in table I, where the first column denotes the system load ρ, the second one shows the blocking probability obtained via simulation, the third one gives the theoretical blocking probability after using the fixed-point approximation of eq. 13, and the fourth column shows the blocking probability given by the Erlang B formula with load $\rho = \frac{\lambda T}{T/D}$:

$$B_{\text{erlang}}(\rho, 1) = \frac{\lambda D}{\lambda D + 1}$$

$\rho = \lambda D$	B_{sim}	$B_{\text{fixed-point}}$	B_{erlang}
0.001	0.0010	0.000914	0.000999
0.005	0.0050	0.0049	0.0050
0.01	0.0099	0.0098	0.0099
0.05	0.0480	0.0470	0.0476
0.10	0.0923	0.0893	0.0909
0.25	0.2061	0.1943	0.2000
0.50	0.3487	0.3204	0.3333
0.75	0.4516	0.4097	0.4286

TABLE I
BLOCKING PROBABILITY RESULTS

As shown, the simulated results are very close to both the fixed-point approximation of eq. 13 and the Erlang-B formula. In fact, the Erlang-B formula provides a closer approximation to the real simulation values, than the fixed-point approximation, especially for large values of ρ.

Indeed, in a single-wavelength switch, the retroblocking effect described in [11] has a very little global effect and does not cause a significant global performance degradation, thus yielding blocking probabilities comparable to the Erlang B formula. This has been shown by an extensive simulation analysis in our previous work [31]. However, the Erlang B formula cannot be applied to distinguish between the "observed" blocking probability of random BCPs with offset time values in the slices $[kT_p, (k+1)T_p]$, $k = 0, \ldots, k_{\text{max}} - 1$ ($k_{\text{max}} = \frac{T}{T_p}$). The next experiment shows this effect and the ability of eq. 14 to capture it.

D. Blocking probability observed by BCP arrivals with different offset times

Fig. 7 shows the blocking probability observed by the BCP arrivals depending on their offset-time values, at scenarios with different load levels. Again, the offset range considered is $[0, 10]$, and $D = 0.15$ is the fixed time spent by constant-size data bursts. The offset range $[0, 10]$ has been divided into $k_{\text{max}} = 10$ chunks of size 1.

For intance, for load level $\rho = 0.01$ (fig. 7 top-left), the blocking values range from 0.0018 to 0.018. Clearly, the BCP arrivals with small offset time values (in the range $[0, 2]$)

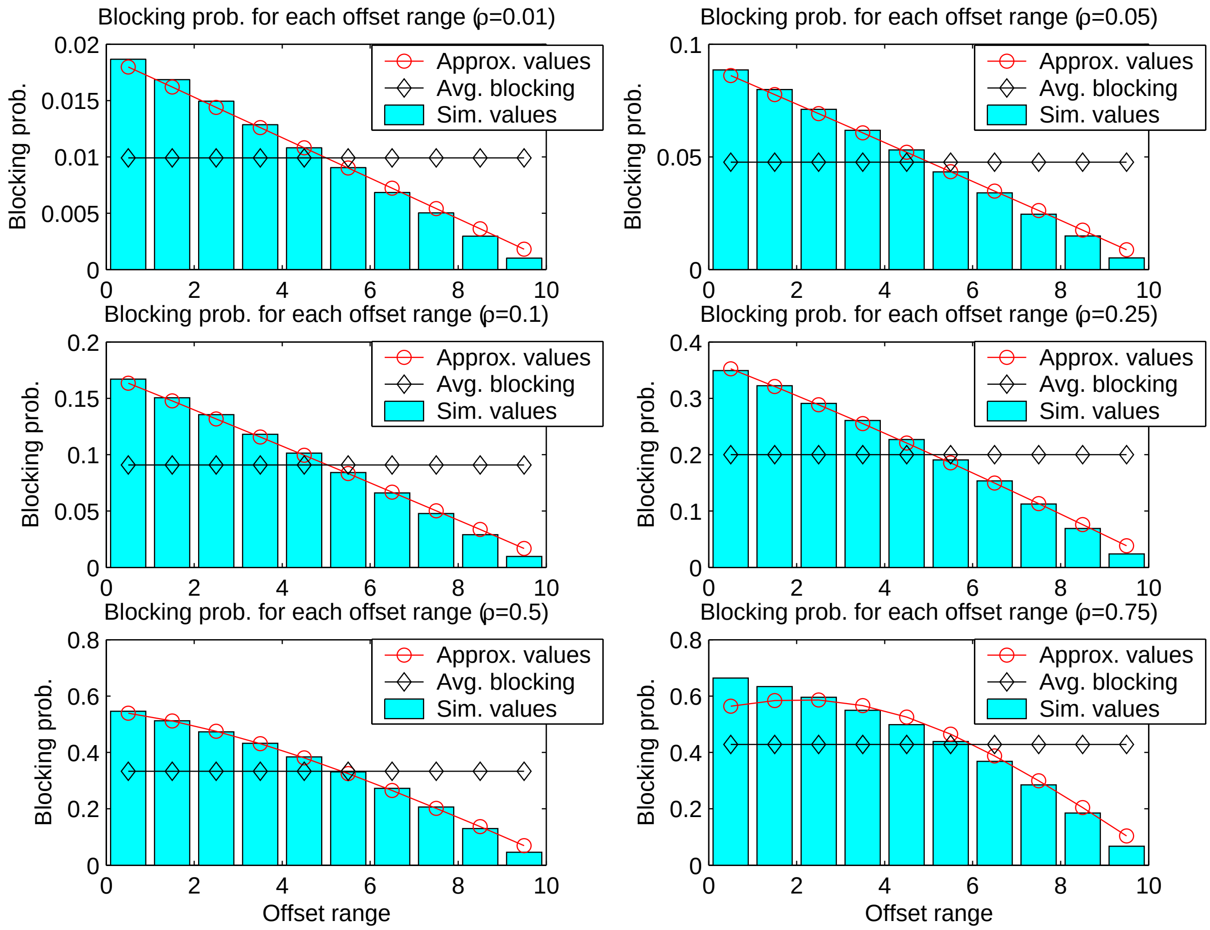

Fig. 7. Blocking probability observed by each offset range in several conditions: $\rho = 0.01$ (top-left), $\rho = 0.05$ (top-right), $\rho = 0.1$ (middle-left), $\rho = 0.25$ (middle-right), $\rho = 0.5$ (bottom-left), and $\rho = 0.75$ (bottom-right)

experience greater blocking probability than those with larger offset values (in the range $[8, 10]$). This tendency is repeated for increasing load levels, as shown in the remaining plots.

It is worth noticing that the analytical curve given by eq. 14 provides a better fit to the simulated results for low load levels than for high load levels. This is consistent with the approximation performed in eq. 14, as the influence of previous reservation in the past-horizon of the tagged burst is smaller with lighter load. Nevertheless, the theoretical curve also gives a close approximation to the observed blocking probability at high load scenarios. Finally, the third line in the figure (continuous with diamonds) provides a measure of the average blocking probability (which is close to the Erlang B values) over the whole range, but does not distinguish between the blocking probabilities observed for "tagged" BCPs with different offset-time values.

IV. Blocking probability equalisation

This section presents a methodology for achieving a flat-shaped plot of fig. 7. That is, with the term *scheduling equalisation*, we shall refer to the mechanism for achieving uniform blocking probability regardless of the offset time values of incoming BCPs, on attempts to provide *fairness* in the process of burst scheduling. The metric f defined as [19]:

$$f = \frac{\max(p_1, \ldots, p_{k_{\max}})}{\min(p_1, \ldots, p_{k_{\max}})}$$

is widely used for measuring such fairness in terms of blocking probability between the different BCP reservations that fall within the range $[kT_p, (k+1)T_p]$, for $k = 0, \ldots, k_{\max} - 1$.

Our approach for blocking probability equalisation follows the proactive discarding policy proposed in the literature [16], [19]. In this light, the methodology is as follows: When a BCP reservation arrives at the core node scheduler, the first step is to check its offset time value, and determine the offset range $[kT_p, (k+1)T_p]$ in which it falls. Once, the value k is known, the next step is to compute the particular blocking probability B_k (as in eq. 14) experienced by BCPs whose offset values fall within such range. With this value, the next step is to calculate the equalisation probability P_{eqz} as:

$$P_{\text{eqz}} = \frac{B_{\text{eqz}} - B_k}{1 - B_k} \quad (16)$$

where B_{eqz} refers to the *targeted overall blocking probability*.

The last step is to take a random number, say r, and check it with P_{eqz}. If $r < P_{\text{eqz}}$, then the packet is dropped (proactive dropping); otherwise, it attempts for a time-slot reservation for it.

Eq. 16 is justified as follows: The probability for any packet to be blocked is given by:

$$B_{\text{eqz}} = P_{\text{eqz}} + (1 - P_{\text{eqz}})B_k \tag{17}$$

which takes into account the proactive dropping probability and the actual blocking probability assuming the BCP is not proactively dropped. It is easy to check that eq. 16 arises from eq. 17. Hence, the probability B_{eqz} is the targeted overall blocking probability since it shows the actual blocking probability experienced by all data bursts.

In this light, fig. 8 shows a case example of a core OBS node fed with $\rho = \lambda D = 0.1$ and with various values of targeted overall blocking probabilities. Fig. 8 top-left shows the plot of blocking probability with respect to the offset range value before any equalisation. At this point, the scheduler presents a fairness coefficient of $f_{\text{bef. eqz.}} = 17.99$ and overall blocking probability $B_{\text{eqz}} = 0.0917$. Fig. 8 top-right shows the blocking plot after equalisation with $P_{\text{eqz}} = 0.5B$, where B is fixed-point solution given by eq. 13. This case equalises part of the blocking plot (those BCPs with higher offset values) achieving $f_{0.5B} = 4.34$ and overall blocking probability $B_{\text{eqz}} = 0.0951$, which is slightly larger than the overall blocking probability before any equalisation technique was adopted (Fig. 8 top-left). This result makes sense since proactive dropping always increases the overall blocking probability. Basically, when dropping bursts proactively, it may well occur that large-offset bursts are dropped on attempts to increase the chances of small-offset bursts to be scheduled, but none of these arrives. So, it often occurs that some bursts are dropped proactively for nothing, thus increasing the overall blocking probability. This effect is specially enhanced at high load levels.

Fig. 8 (middle-left) shows a case where $P_{\text{eqz}} = 1B$ leading to a more fair plot with $f_{1B} = 1.99$, but with overall blocking probability $B_{\text{eqz}} = 0.1089$. The remaining plots in Fig. 8 shows cases where almost complete fairness ($f \approx 1$) is achieved, however at the expense of substantially higher blocking probabilities. A summary of the fairness values, together with the overall blocking probabilities, for the equalisation of the case example explained above with different targeted blocking probabilities is given in fig. 9.

As shown, the fairness coefficient defined in eq. 16 decreases the larger the value of B_{eqz} is, leading to very flat blocking probability plots, as shown in fig. 8. However, this is at the expense of a significant increase in the overall blocking probability as shown. As shown, a good trade-off could be the choice of $B_{\text{eqz}} \in [1B - 1.5B]$ which does not increase the overall blocking probability too much and achieves fairness coefficients in the range $f \in [1, 2]$, which are characteristic of flat blocking probability plots similar to the one shown in fig. 8 middle-left.

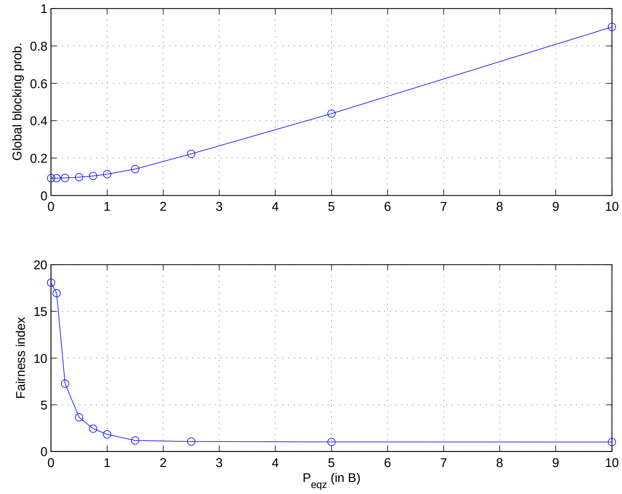

Fig. 9. Summary of overall blocking probability (top) and fairness values (bottom) for several B_{eqz} values in a scenario with $\rho = 0.1$.

V. Summary and Discussion

This work presents a study of the blocking probability observed by BCP arrivals with continuous-time uniformly-distributed offset times in a single-wavelength core OBS node (or a core OBS without wavelength conversion capabilities). As previously reported by the research community, the BCP reservations arriving with large offset values typically suffer less blocking than those arrivals with small offset-time values, which produces the so-called Path Length Priority Effect. The contribution of this work is to quantify the difference in terms of blocking probability perceived by the BCP reservations with offset-time which are *uniform* in a range of values. Note that this is a *continuous case* which differs from the discrete case that has been reported elsewhere [13], [20].

As a result, a fixed-point equation is derived which brings the blocking probability experienced by a tagged BCP with uniformly-distributed offset range. This result is then applied to quantify the blocking probability experienced by a given tagged BCP whose offset falls in a particular range within the maximum offset range. The analytical values are shown to accurately approximate the simulation results.

As a possible application, this work proposes a proactive descarding policy to achieve an equalised plot of the blocking probability regardless of the particular offset values of incoming BCPs. The mechanism proposed is designed such that incoming BCPs are proactively descarded with greater probability the larger its offset-time value is, which reduces the number of reservations with large offset times on attempts to benefit those BCP arrivals with small offset values. The experiments section shows that, although this mechanism increases the overall blocking probability, a good level of fairness can be achieved at the expense of moderate increase in the global blocking probability.

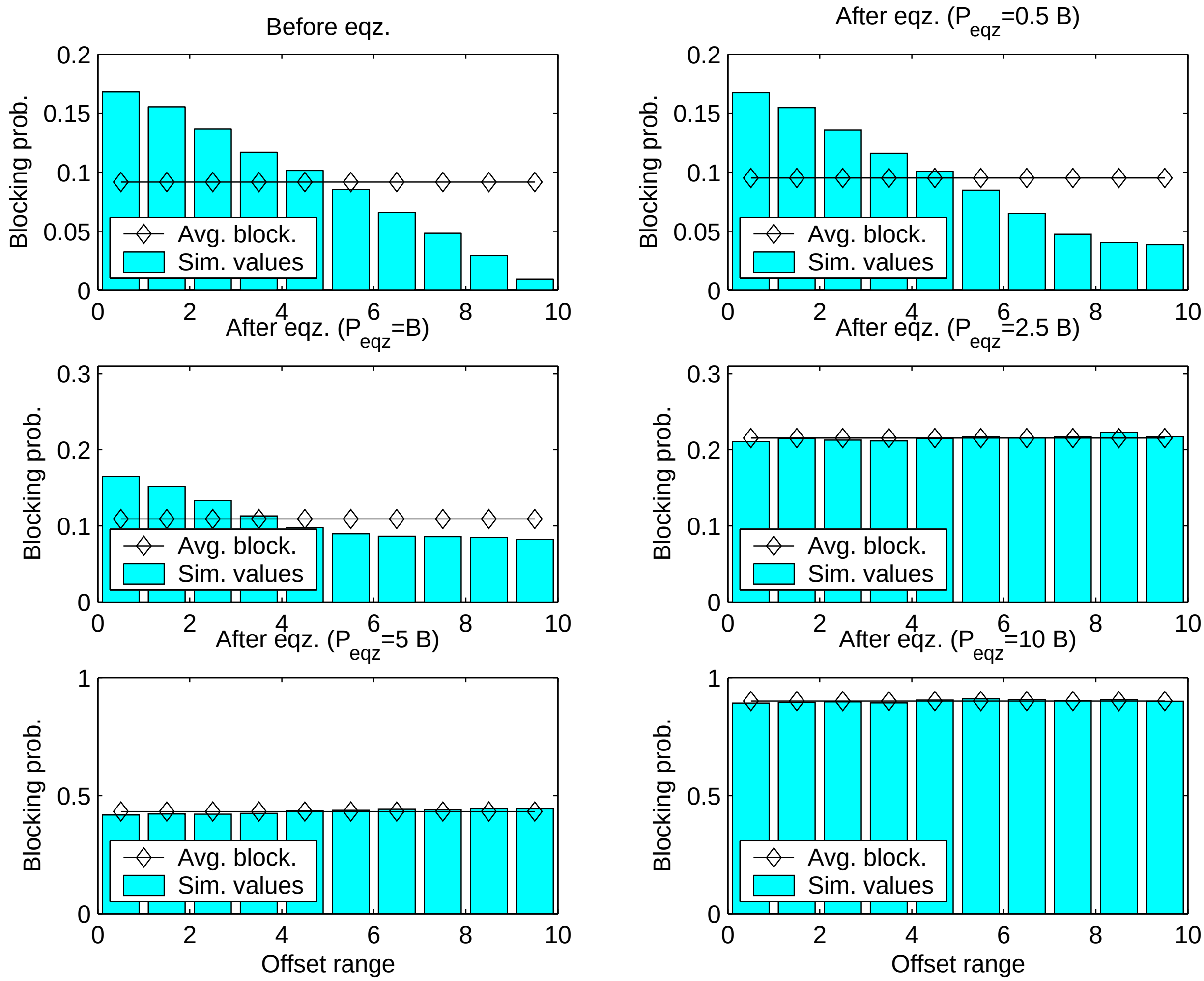

Fig. 8. Blocking probabilities before and after equalisation with different targeted blocking probabilities: Before equalisation (top-left); After equalisation with $B_{\text{eqz}} = 0.5B$ (top-right); After equalisation with $B_{\text{eqz}} = 1B$ (middle-left); After equalisation with $B_{\text{eqz}} = 2.5B$ (middle-right); After equalisation with $B_{\text{eqz}} = 5B$ (bottom-left); and, After equalisation with $B_{\text{eqz}} = 10B$ (bottom-right).

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