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Dropping Probability Reduction in OBS Networks: A Simple Approach

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Abstract—In this paper, we propose and derive a slotted-time model for analyzing the burst blocking probability in Optical Burst Switched (OBS) networks. We evaluated the immediate and delayed signaling reservation schemes. The proposed model compares the performance of both just-in-time (JIT) and just-enough-time (JET) signaling protocols associated with of void/non-void filling link scheduling schemes. It also considers none and limited range wavelength conversions scenarios. Our model is distinguished by being adaptable to different offset-time and burst length distributions. We observed that applying a limited range of wavelength conversion, burst blocking probability is reduced by several orders of magnitudes and yields a better burst delivery ratio compared with full wavelength conversion.

Key Words: Slotted time model, Optical burst switching, Just in time, Just enough time, Blocking probability.

I. INTRODUCTION

One of the most widely adopted all-optical switching technologies in the current commercial carrier networks is based on circuit-switching, in which a light path is setup between two switches for a relatively long period of time. In such a network, also called a wavelength-routed (WR) network, the light paths provisioned along fibers are switched according to their wavelengths. Basically, the WR approach is not efficient when traffic is bursty and variant with time since a WR light path is a bandwidth guaranteed tunnel, with which any variation in the effective data transmission may easily lead to either inadequacy or waste of the allocated bandwidth.

Optical Burst Switching (OBS) [1-9] is a promising alternative for the future optical network data plane to deal with the bursty and dynamic Internet traffic with high efficiency. OBS takes a data burst as a basic switching granularity composed of a group of IP packets switched together from one ingress node to another. With OBS, a control packet must be sent by the ingress along the predefined physical route to configure the switch fabrics of each intermediate node in prior to the arrival of the data burst to ensure a precise cut-through at each intermediate switch for the data burst that is transparent to the control layer. The period between the moments of sending the control packet and that for its corresponding optical data burst is called offset-time. Each intermediate switch is explicitly notified of the arrival and the departure time of the corresponding data burst.

The two well-known schemes for resource reservations at the intermediate switches are either delayed or explicit reservation schemes. Just-Enough-Time (JET) [1, 2] and Just-In-time (JIT) [10, 11] are the two most adapted practical implementations of the reservations schemes in OBS [1]. In spite of numerous advantages, OBS has also inevitably introduced some side effects that impair the quality of service (QoS), such as the buffering delay at edge nodes, random burst contention due to one-way signaling reservation protocol, and frequent retro-blocking. Burst dropping has the most negative impact from the upper layers perspective, which requires burst retransmission and resultant delay increase.

In OBS network, burst dropping occurs due several reasons such as, burst contention, link congestion, link reservation algorithm, and retro-blocking. The literature is rich in many interesting burst dropping probability models that have been proposed to evaluate burst dropping in different conditions. For JIT signaling, the output port is modeled as an M/G/k/k queue and using Erlang's-B loss probability formula, the burst dropping is obtained.

In [12], Two-state Markov Chain model is used to approximate the packet loss for JET signaling using First-Fit with Void Filling (FF-VF) as a link scheduling algorithm. In [13], a dropping probability model is obtained while considering different FDLs buffering granularities. In [14, 15], a burst dropping probability model is derived considering burst retransmission and burst deflection routing schemes. In [16], an enhanced version of JET is proposed, called Virtual Fixed Offset Time (VFO), which process the burst based on their actual arrival time. In [17], another enhancement of JET called Slotted JET (S-JET) is proposed to improve the processing time for JET when reservation takes place at the end of the reservation list. L. Andrew et al. [18] derived an asymptotically condition for zero blocking probability considering different number of wavelengths. This helps in identifying regions where a low dropping probability exists.

F. J. Vázquez-Abad et al. [19] closely modeled and examined the effect of offset-time. They derived a model that presents the distribution of offset times as a function of the control packet header length. They have also proved that the variance of this distribution affects the overall network burst dropping probability. A lower-bound threshold is derived for the header length, where the dropping becomes less sensitive to the reservation algorithm. In [20], N. Barakat, T.E. Darcie performed a detailed analysis of the effects of control-plane processing on the network throughput performance of OBS networks. An analytical model is derived to capture the effect of the control header queuing process in core nodes. The study found that ultrafast control-packet processing speed is not necessary for efficient OBS operation. Instead, they pointed that in current long-haul networks, the average end-to-end control latency can be hundreds of times larger than is the header processing delay.

In [21], a stochastic model for obtaining burst dropping probability for optical burst switching network utilizing wavelength converter sharing is derived. The model considers the burst arrival as Markovian arrival process to cope with different traffic

patterns. The burst length is assumed to be exponentially distributed. In [22], an optimal burst scheduling algorithm is proposed. The proposed scheduling algorithm relies on constant time burst re-sequencing scheme. The scheme basically removes the variability in offset-times. Therefore, the offset-time-based priority schemes cannot be supported. The burst contention and dropping probabilities are studied in the presence of different routing algorithms [23]. V. Tintor, P. Matavulj [24], proposed a reduced load fixed-point approximation model to evaluate burst dropping probability. The model considers both JIT and JET associated with burst segmentation and route-dependent priorities. The study showed that burst segmentation yields the lowest dropping probability. The route-dependent priority improves the overall dropping probability but not significantly.

The above proposed studies mainly aim to reduce the burst dropping probability and consequently to enhance the network throughput. In this paper, an analytical model is derived for OBS networks performance enhancement considering both the JIT and JET signaling protocols, number of input wavelengths, burst offset-time and burst-length distributions, and burst contention resolution techniques. We extend the work presented in [25] by using variable burst lengths to analyze the performance of OBS network using JIT and JET signaling protocol. We also investigated the effect of limited range wavelength conversion on network performance.

The rest of this paper is organized as follows. In section II, model assumptions and parameters are introduced. Section III presents the developed traffic model for evaluating JIT with no-wavelength conversion and with a limited range wavelength conversion. Section is devoted to detailed analysis of JET with void filling and no-wavelength conversion, without void filling and no-wavelength conversion, and truncated. Section V shows and discusses the numerical results of the developed models and model validation through a logical comparison between suggested models. This is followed by main concludes in Sec. VI.

II. TRAFFIC MODEL

In this section, we present the general considerations, concepts and definitions that are vital for our analysis. In order to develop a tractable model, we assume that the time is divided into slots each of duration T_s . It is also assumed that both the offset time (a) and the burst duration (b) are integer multiples of time slot duration T_s . Since both offset time and burst duration are random variables, one can define L_a as the average offset time and L_b as the average burst duration. Thus, one can define L as the mean of the random variables a+b

$$L = L_a + L_b \quad (1)$$

In OBS, optical bursts and/or control packets arrive to an OBS node with a rate R_b bursts/s. In addition, the arrival stream follows a Poisson process. Thus, the probability, $P_b(m)$ that m bursts arrive to an OBS node during any time slot follows a Poisson distribution [1]

$$P_b(m) = e^{-R_b T_s} \frac{(R_b T_s)^m}{m!}, \quad m \in \{0, 1, 2, \dots\} \quad (2)$$

Since the time slot duration T_s is very small such that $P_b(m) \cong 0$ for $m \geq 2$, then, Eq. (2) can be reduced to

$$P_b(m) = \begin{cases} e^{-R_b T_s} \cong 1 - A, & \text{if } m = 0 \\ R_b T_s e^{-R_b T_s} \cong A, & \text{if } m = 1 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

where A denotes the probability that a burst arrives within a time slot, which is also referred as the network load [25]. The approximation in Eq. (2) is valid when $R_b T_s$ is very small. Accordingly, T_s should be tuned according to bursts arrival rate.

Moreover, the load is assumed to be distributed uniformly on wavelength channels. Thus, the probability that the arriving burst requests on a particular wavelength is A/W where W is the number of wavelength channels. Thus, the network traffic (k) is defined as

$$k \stackrel{\text{def}}{=} AL \text{ bursts/burst time} \quad (4)$$

III. JUST-IN-TIME MODEL

This JIT model is used to evaluate the burst blocking probability under considering no-wavelength conversion is employed with variable burst sizes.

A. JIT without Wavelength Conversion

Since there is no-wavelength conversion, each wavelength channel is expected to evolve independent of the others with load A/W . The sum of offset time and burst duration is assumed to be geometrically distributed with a mean L .

Let $X_i^{(n)}$ represents the state of wavelength i during the time slot n , where $i \in \{1, 2, \dots, W\}$. If the wavelength is busy, then $X_i^{(n)} = 1$, and otherwise $X_i^{(n)} = 0$. The process $\{X_i^{(n)}\}$ is a two-state Markov chain with the following transition probability matrix [26]

$$Q_i = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \quad (5)$$

with the transition probabilities defined as

$$p_{jk} = P(X_i^{(n+1)} = k \mid X_i^{(n)} = j) \quad j, k = 0, 1 \quad (6)$$

Since the load A is uniformly distributed on wavelength channels, all channels have the same transition probability matrix which is referred as Q . In the steady state, the probability that a wavelength channel is busy is given by

$$\pi_1 = P(X_i = 1), \quad (7)$$

and the idle probability is given by

$$\pi_0 = P(X_i = 0) \quad (8)$$

For the JIT without wavelength conversion (JIT-NWC), the single channel transition probability matrix is given by

$$Q = \begin{bmatrix} 1 - A/W & A/W \\ q(1 - A/W) & 1 - q(1 - A/W) \end{bmatrix} \quad (9)$$

where $q = 1/L$.

The steady state distribution is given by

$$\pi_0 = \frac{(W - A)q}{(W - A)q + A}, \quad (10-a)$$

$$\pi_1 = \frac{A}{(W - A)q + A} \quad (10-b)$$

Since all wavelength channels might be at state 0 or state 1, the output link state is defined by the binary vector $Z = [X_1, X_2, \dots, X_W]$. It is noted that, there are 2^W states divided into $(W+1)$ classes. The probability that the output link in some binary state z_i ($P(z_i)$) is given by

$$P(z_i) = \pi_1^{m_i} \pi_0^{W-m_i}, \quad 0 \leq i \leq 2^W - 1 \quad (11)$$

where m_i is the number of busy channels in state z_i .

Data burst is blocked if the wavelength channel is busy during the time slot of the arrival of the control burst and is still busy in the next time slot. The blocking probability, B , of the system is [26]

$$B = \sum_{i=0}^{2^W-1} P(z_i) \frac{m_i A}{W} (1 - q),$$

which can be reduced to

$$B = \sum_{i=0}^W \binom{W}{i} \pi_0^{W-i} \pi_1^i \frac{iA}{W} (1 - q) \quad (12)$$

After some algebraic manipulation, B can be written as

$$B = A(1 - q)\pi_1 \quad (13)$$

B. JIT with Limited Range Wavelength Conversion

In limited range wavelength conversion, data bursts arriving on a busy wavelength channel can be converted into a fixed set of wavelength channels above and below the original wavelength [27-29]. The degree of conversion (d) defines the number of

target wavelengths for conversion on either side of the original wavelength data channel. If a burst arrives to a channel i , there are two cases: (1) channel i is idle, so that no wavelength conversion occurs, (2) channel i is busy, so that wavelength i is converted to the nearest idle wavelength among d channels on either side of i , which means that, the OBS switch is aware of each channel state. If both the equi-nearest wavelength channels are idle, conversion is done randomly with a probability $1/2$. Recall, data burst arrives to channel i is blocked if channel i is busy ($X_i=1$) and there is a sequence of busy channels of length d on either sides of channel i provided that, all of them are still busy in the next time slot. Thus, one defines (C_i) as the number of blocking channels in case of state z_i .

The traffic motion in JIT with a limited range wavelength conversion (JIT-LRWC) for $d=1$ is displayed in Fig. 1. The mutual traffic between each pair of wavelength channels is cancelled by each other. Therefore, each wavelength channel evolves independently from the others with its outer incoming traffic rate. The main difference of the outer incoming traffic and the mutual traffic is that, the outer incoming traffic is trying to find a place on its distained channel, while the mutual traffic guarantees its place on a substitute channel due to OBS switch awareness of each channel state.

By the aid of the last assumption, one can use the same single channel model given in Sec. III.

The blocking probability of this system is evaluated as

$$B = \sum_{i=0}^{2^W-1} P(z_i) \frac{C_i A}{W} (1-q)^{2d+1}, \quad (14)$$

which can be reduced to

$$B = \sum_{i=0}^{2^W-1} \pi_1^{m_i} \pi_0^{W-m_i} \frac{C_i A}{W} (1-q)^{2d+1}, \quad (15)$$

where C_i is determined during the numerical calculations by examining the elements of state z_i along with the degree of conversion.

IV. JUST-ENOUGH-TIME MODEL

In JET, a control packet contains the data burst duration (b) and the burst-offset time (a). The main difficulty in modeling the JET signaling scheme (i.e., advance resource reservation schemes), is that certain reservation request can be blocked by a reservation starting only after its own start time. This phenomenon of “retro-blocking” becomes significant since notice dispersion becomes larger [12].

A. JET with void filling and no-wavelength conversion

Since there is no-wavelength conversion, each channel is assumed to evolve independently from each other. We assume that, both the offset-time and burst duration are geometrically distributed with mean $(1/r)$, $(1/q)$, respectively, such that

$$\begin{aligned} f(a) &= (1-r)^{a-1} r, \quad a = 1, 2, 3, \dots, \\ g(b) &= (1-q)^{b-1} q, \quad b = 1, 2, 3, \dots \end{aligned} \quad (16)$$

The JET with void filling (JET-VF) is shown in Fig. 2.

Given that offset-time is (a) and burst duration is (b), the blocking probability, $B(a, b)$, can be evaluated by using the retro-blocking phenomenon. In other words, any request might be blocked by a previous request reserving some of time slots $\{a+1, a+2, \dots, a+b\}$ considering that request arrives at a time slot 0 without loss of generality.

One observes that in order to block a request arriving at a time slot 0 trying to reserve the channel after an offset time (a) for a burst duration (b), there must be a previous request at a certain time slot ($-i$) that had reserved any of the time slots $\{a+1, a+2, \dots, a+b\}$. Hence, $B(a, b)$ can be evaluated as

$$B(a,b) = \frac{A}{W} \sum_{i=1}^{\infty} p(a+i \leq \text{offset} \leq a+b+i-1) + \quad (17)$$

$$p \left(\begin{array}{l} 1 \leq \text{offset} < a+i \cap \\ a+i+1 \leq \text{offset} + \text{burst duration} \leq a+b+i \end{array} \right).$$

Using Eq. (16), Eq. (17) becomes

$$B(a,b) = \frac{A}{W} \left[\frac{(1-(1-r)^b + \frac{r(1-q)(1-(1-q)^b)}{(q-r)}) (1-r)^a}{r} - \frac{r(1-q)(1-(1-q)^b)(1-q)^a}{(q-r)q} \right] \quad (18)$$

The single channel blocking probability, B_c , is [26]

$$B_c = \frac{A}{W} \sum_{a=1}^{\infty} \sum_{b=1}^{\infty} r(1-r)^{a-1} q(1-q)^{b-1} B(a,b) \quad (19)$$

Consequently, the system blocking probability is

$$B = WB_c \quad (20)$$

B. JET without Void Filling and No-Wavelength Conversion

The analysis of non-void filling scheduling algorithms is simpler than void filling algorithms since the acceptance of a burst request only depends on the offset-time of the burst and its unscheduled time. In other words, a request is accepted if the burst start time is after the end time of last reserving burst. Figure 3 illustrates the non-void filling scheme.

The non-void JET (JET-NVF) single channel process is a Markov chain with state transition diagram shown in Fig. 4. The only wavelength channel that can be considered eligible by non-void filling algorithms is channel 4, since it is the only wavelength that is unscheduled on or after time t_a . The state of the wavelength channel is the remaining time to be free (T). The burst request is blocked if its offset time (a) is less than the remaining time to be free (T). Similar to the previous section, we assume that both the offset time and burst duration are geometrically distributed with a mean $(1/r)$ and $(1/q)$, respectively. So, $f(a)$ and $g(b)$ follow Eq. (16).

The transition probabilities are given by

$$P_{ij} = \frac{A}{W} \sum_{k=i}^j P(a=k) p(b=j-k+1), \quad j > i$$

$$= 1 - \frac{A}{W} + \frac{A}{W} P(a < i), \quad j = i - 1$$

$$= \frac{A}{W} P(a = i) P(b = 1), \quad j = i$$

$$= 0 \quad \text{elsewhere}$$

(21)

By the aid of Eq. (16), the last equation reduces to

$$P_{ij} = \begin{cases} \frac{A}{W} r(1-r)^{i-1} q(1-q)^{j-i} \frac{\left(\left(\frac{1-r}{1-q}\right)^{j-i+1} - 1\right)}{\left(\left(\frac{1-r}{1-q}\right) - 1\right)}, & j > i \\ 1 - \frac{A}{W} (1-r)^{i-1}, & j = i-1 \\ \frac{A}{W} r(1-r)^{i-1} q, & j = i \\ 0 & \text{elsewhere} \end{cases} \quad (22)$$

In order to find the steady state distribution, we have to solve a system of infinite linear equations. Unfortunately, the system of infinite linear equations is not solvable analytically. So, the following section presents our system truncation analysis.

C. Truncated JET without Void Filling and No-Wavelength Conversion

We truncate the infinite process by setting maximum values for both the offset time (M) and burst duration (N) such that $M = \min\{i: p(a > i) < \varepsilon_a\}$, $N = \min\{i: p(b > i) < \varepsilon_b\}$. The truncated process is shown in Fig. 5. The figure shows that the maximum number of states will be (M+N).

In order to find the transition probabilities, one defines the two quantities

$$\min l = \max(i, j+1, 1-N) \quad (23-a)$$

and

$$\max l = \min(j, M) \quad (23-b)$$

Using Eq. (23), the transition probabilities become

$$P_{ij} = \begin{cases} \frac{A}{W} \sum_{k=\min l}^{\max l} P(a=k) P(b=j-k+1), & j > i, 1 \leq i \leq M \\ \frac{A}{W} P(a=i) P(b=1), & j = i, 1 \leq i \leq M \\ 1 - \sum_{k=i}^{M+N-1} P_{ik}, & j = i-1, 1 \leq i \leq M \\ 1, & j = i-1, M < i \leq M+N-1 \\ P_{1j}, & 0 \leq j \leq M+N-1, i=0 \\ 0, & \text{elsewhere.} \end{cases} \quad (24)$$

Using Eq. (16), one can get

$$p_{ij} = \begin{cases} \frac{A}{W} r(1-r)^{\min l-1} q(1-q)^{j-\min l} \times \frac{\left(\left(\frac{1-r}{1-q}\right)^{\max l-\min l+1} - 1\right)}{\left(\frac{1-r}{1-q}\right) - 1} & j > i, 1 \leq i \leq M \\ \frac{A}{W} r(1-r)^{i-1} q, & j = i, 1 \leq i \leq M \\ 1 - \sum_{k=i}^{M+N-1} p_{ik}, & j = i-1, 1 \leq i \leq M \\ 1, & j = i-1, M < i \leq M+N-1 \\ p_{0j} = p_{1j}, & 0 \leq j \leq M+N-1 \\ 0, & \text{elsewhere} \end{cases} \quad (25)$$

The steady state distribution of the remaining time to be free (T) can be obtained by solving the system of linear equations under the condition $\sum_{k=0}^{M+N-1} \pi_k = 1$. The channel blocking probability (B_c) is given by

$$B_c = \frac{A}{W} \left((1-r)^M + (1-q)^N - (1-r)^M (1-q)^N \right) + \frac{A}{W} (1-(1-q)^N) \sum_{k=1}^M r(1-r)^{k-1} \left(\sum_{i=k+1}^{M+N-1} \pi_i \right) \quad (26)$$

Equation (26) is used in Eq. (20) to obtain the system blocking probability (B).

V. NUMERICAL RESULTS

In this section, we validate the obtained results through a logical comparison to previous studied models.

A. JIT Model Validation

In order to validate our JIT without wavelength conversions, model presented in Sec. III.A, a comparison will be carried out with the model with fixed length bursts given in [29]. Figure 6 shows that the proposed model, which considers a geometric distributed burst length with a mean equals 500 time slot, gives identical results to the model given in [29].

This observation might be surprising since we expect our model to give a better performance since it deals with a variable burst length. However, the result symmetry is mainly due to the memoryless property of the geometric distribution. In other words, if the channel is busy, it will accept the incoming arrival if the current time slot is the burst last time slot. The probability to find the burst last time slot equals q in case of geometric distribution and equals $(1/\text{burst length})$ in case of fixed length burst. If we select the geometric distribution with mean equals to the fixed burst length, we will obtain the same blocking probability.

Figure 7 displays the blocking probability of JIT with limited range wavelength conversion presented in Sec. III.B considering $d=1$ and 2. We compare the model with JIT without wavelength conversions.

It is obvious that the blocking probability has been improved due to relaxing the condition of no-wavelength conversion. Also, we observe that the system becomes less sensitive to the load when the degree of conversion (d) is increased.

B. JET Model Validation

Figure 8 shows the validation of the JET with void filling (JET-VF) model.

It can be seen that JET-VF gives a lower blocking probability than JIT without wavelength conversion. Also, it is observed that both curves are close to each other at a lower load, but the gap becomes wider at a higher load. This is mainly due to the nature of both JET-VF scheme which allows delayed reservations and void filling, while JIT without wavelength conversion allows immediate reservations and ignores any requests while the channel is busy.

Figure 9 compares the blocking probability of JET-VF and JET and JET-NVF at a relatively small mean of offset-time ($r = 0.9$). It is observed that the two curves are close to each other, especially at lower and higher network load.

C. Bernoulli Arrivals vs. Poisson Arrivals

The proposed model in [30] suggests a maximum number of arrivals per time slot to be two instead of one as in [29]. The authors attempted to give better approximation to Poisson distribution. They proposed the formula

$$P_b(m) = \begin{cases} e^{-R_b T_s} \cong 1 - A + \frac{A^2}{2} = p_0, & \text{for } m = 0 \\ R_b T_s e^{-R_b T_s} \cong A - \frac{A^2}{2} = p_1, & \text{for } m = 1 \\ \frac{(R_b T_s)^2}{2!} e^{-R_b T_s} \cong \frac{A^2}{2} = p_2, & \text{for } m = 2 \\ \frac{(R_b T_s)^m}{m!} e^{-R_b T_s} \cong 0 & \text{otherwise,} \end{cases} \quad (27)$$

where the network load A is given by

$$A = R_b T_s \quad (28)$$

The authors justified that their model and gives more accurate results as they considered the case of two simultaneous arrivals. From our point of view, we see that the JIT without wavelength conversion will not be affected in this case as one of the two simultaneous arrivals will be blocked anyway. We argue that their model gives more accurate results as their network load is $\exp(R_b T_s)$ multiple of our network load given in Eq. (3). In order to compensate this difference to find the blocking probability, we modified our blocking probability formula given by Eq. (13) to be

$$B = A(1 - q)\pi_1 + \frac{1}{2}p_2, \quad (29)$$

We see that the results of Eq. (29) shown in Fig. 10 are similar to those in [30]. We notice that, the effect of adding the term $(0.5 p_2)$ decreases with the increase of $R_b T_s$.

D. Effect of Number of Wavelengths

The effect of increasing the number of wavelengths on the blocking probability is shown in Fig. 11. The figure shows a comparison between JIT without wavelength conversion and JIT with limited range wavelength conversion. Both schemes give a lower blocking probability at higher number of wavelengths.

To emphasize our point of view, Fig. 12 shows the blocking probability ratio of JIT without wavelength conversion and JIT with limited range wavelength conversion ($d=1$). It shows that the ratio decreases rapidly with the number of wavelengths. In other words, in realistic WDM systems with a large number of wavelengths, JIT with a limited range wavelength conversion is expected to give much better performance than JIT without wavelength conversion. A question about cost might come to the mind since the large number of wavelengths implies larger number of limited range wavelength converters and consequently more expenses. The answer is that, the larger the number of wavelengths is the smaller tuning range of converters, which means more but cheaper converters.

E. Effect of Degree of Conversion

The blocking probability is plotted in Fig. 13 versus the relative degree of conversion ($2d/W$) considering a fixed load of 0.5 and a number of wavelengths of 16. It is observed that the blocking probability improves rapidly with the increase of d . This is due to the fact that the incoming traffic will have more chance to be accepted if one allows a conversion range to accommodate more neighbor wavelengths, which means a higher degree of conversion. One interesting observation is that, at higher degree of conversion, the blocking probability decrease rate is smaller at lower degrees of conversion. We also notice that a limited range wavelength conversion gives close and less expensive results than full wavelength conversion.

F. Effect of Offset Time and Burst Length

In this section, the effect of offset-time and burst duration on performance of JET is studied in both void filling and non-void filling scheduling algorithms. Figure 14 shows the blocking probability versus the ratio of offset time to burst duration considering the mean of sum of offset time and burst duration (L) to be fixed for both void filling and non-void filling cases.

For both cases, the blocking probability decreases along with offset time increase. This is due to the wider gaps created that help a delayed reservation scheme as JET to find places for short and early coming bursts. One can also see that, the blocking rate (slope) decreases with offset time for the same reason.

Comparing both scenarios of void filling, it is clear that JET with void filling has a significant lower burst blocking rate compared to JET without void filling. As the offset time increases, the performance differentiation becomes clearer. Moreover, JET without void filling, the value of blocking probability saturates with higher q/r ratio. On the other hand, JET with void filling continues to make use of increased offset time by accommodating short bursts and hence reduces the blocking probability.

G. JIT vs. JET Burst Dropping Probability

In Fig. 15, we evaluate both JIT and JET. Considering the condition, where no wavelength conversion is employed, JET outperforms JIT with limited range wavelength conversion.

On the other hand, JIT with limited range wavelength conversion outperforms JET with void filling. Therefore, although wavelength conversion increases the system cost, it helps the system to gain better performance. From our point of view, a limited range wavelength conversion gives good results and also provides economic and industrial solution to be carried out in near future.

VI. CONCLUSION

In this work, we proposed a slotted-time model aiming to analyze the performance of OBS network signaling schemes and burst scheduling algorithms. The analysis methodology depends on using Markov chains to evaluate the burst blocking probability. Four scenarios of OBS scheduling schemes have been evaluated. It is shown that JIT without wavelength conversion gives the highest blocking probability among the studied schemes.

JIT with a limited range wavelength conversions performance increases rapidly with the number of wavelengths and also with the degree of conversion. It is considered a suitable solution to implement a practical OBS network in near future. JET without void filling gives a moderate performance when compared to both JIT with limited wavelength conversion and JET with void filling. We also showed that for a relatively short offset-time, the performance of JET with and without void filling are very close to each other. The performance is mainly affected by the number of wavelengths. Burst blocking probability is reduced by several orders of magnitudes and yields a better burst delivery ratio compared with full wavelength conversion.

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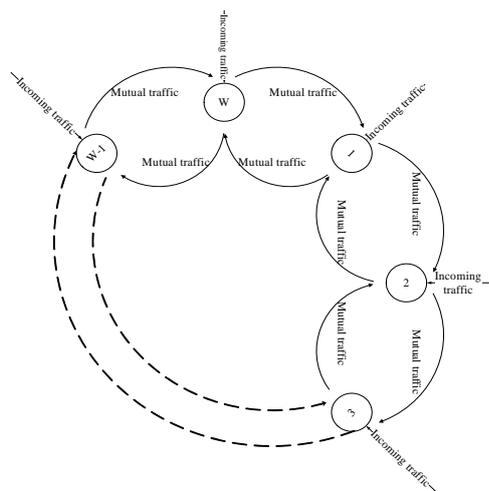


Fig. 1 Traffic motion in JIT with a limited range wavelength conversion for $d=1$.

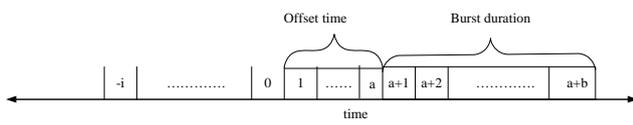


Fig. 2 JET with void filling.

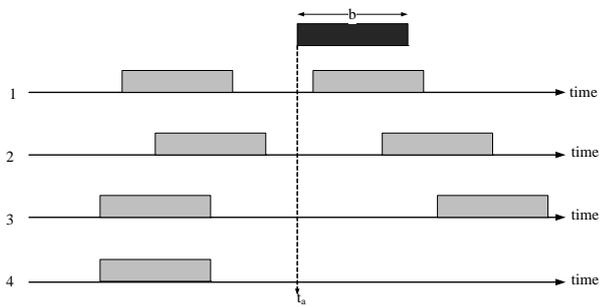


Fig. 3 Wavelength channel scheduling without void filling.

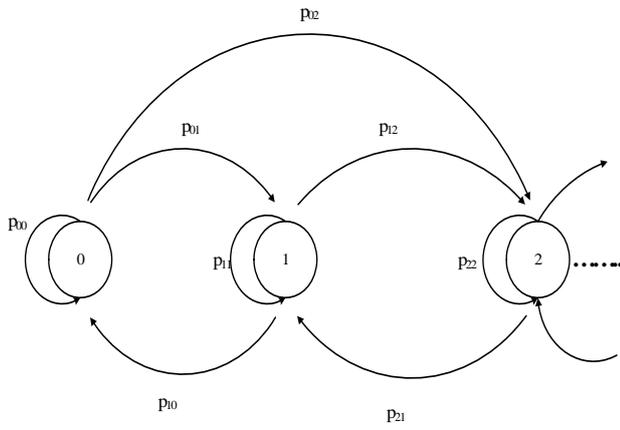


Fig. 4 Non-void JET single channel process.

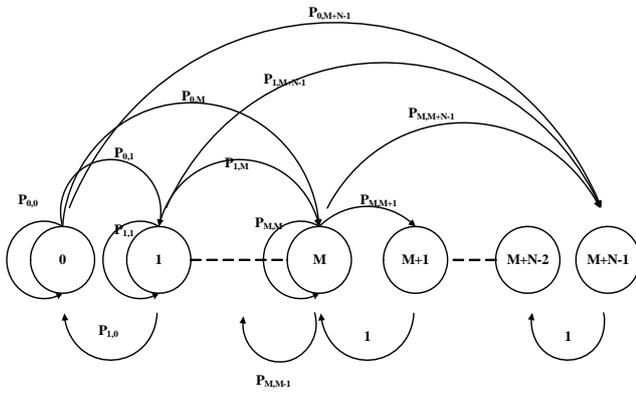


Fig. 5 Truncated non-void filling JET single channel process.

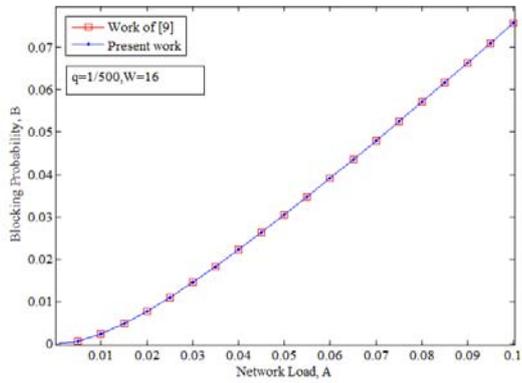


Fig. 6 JIT burst blocking probability without wavelength conversions.

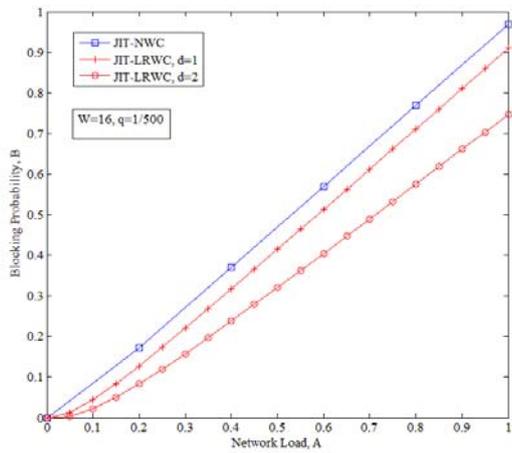


Fig. 7 JIT burst blocking probability with limited range wavelength conversion.

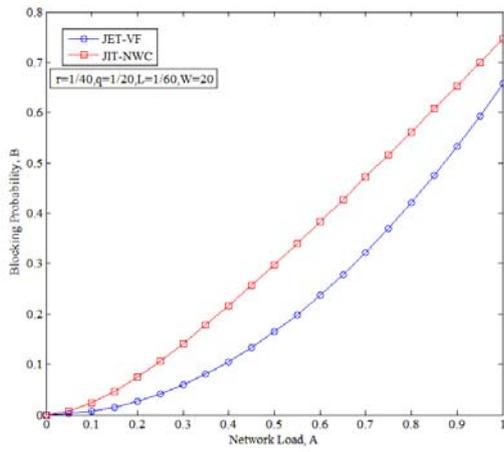


Fig. 8 JET burst blocking probability with void filling.

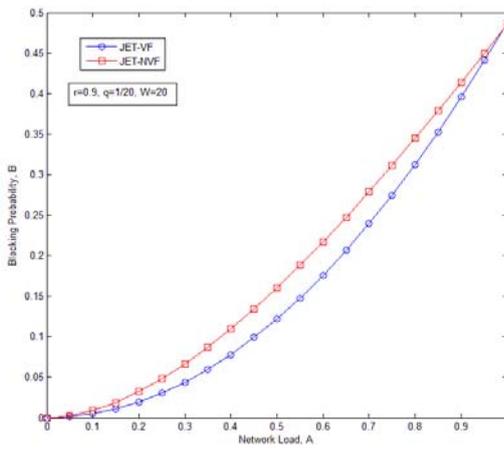


Fig. 9 JIT-VF and JET-NVF blocking probability with small offset time.

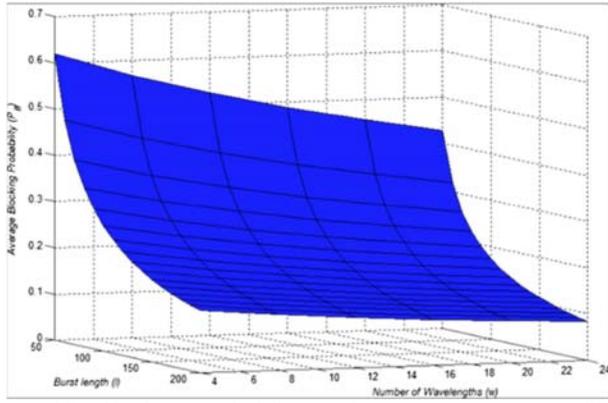


Fig. 10 Blocking probability with compensation at $K=30$.

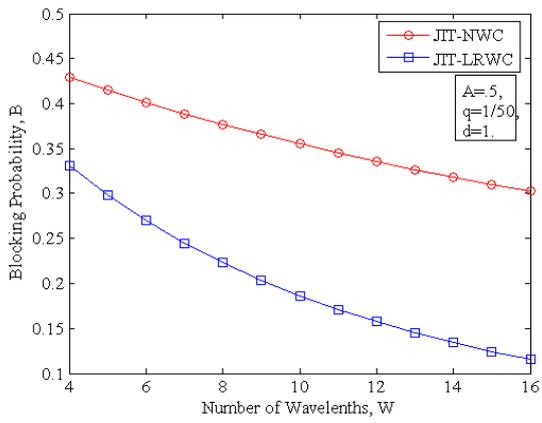


Fig. 11 Blocking probability versus number of wavelengths.

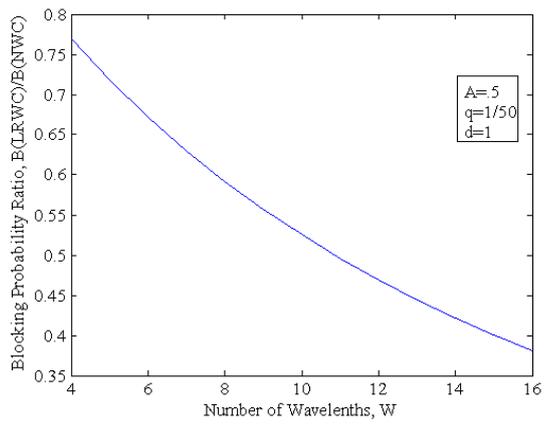


Fig. 12. Blocking probability ratio.

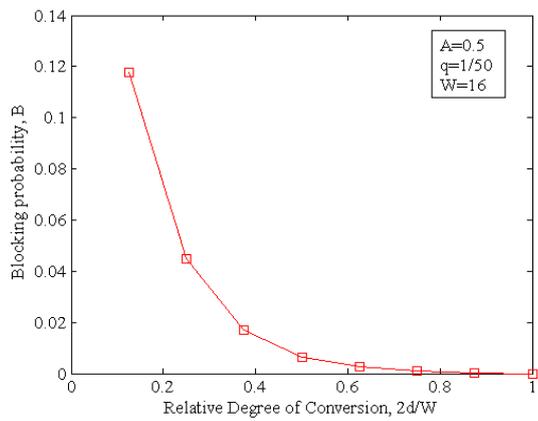


Fig. 13 Blocking probability versus relative degree of conversion (d).

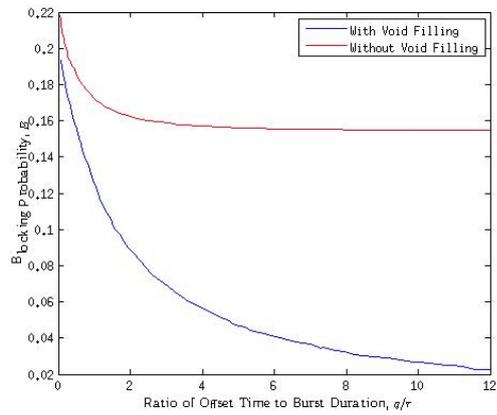


Fig. 14 JET blocking probability with fixed L ($A=0.5$, $W=40$, and $L=65$).

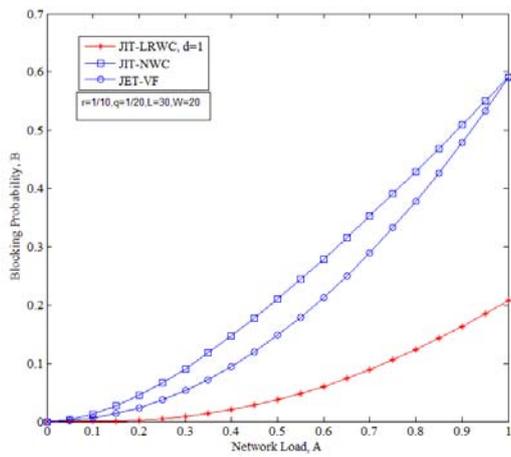


Fig. 15 JIT and JET burst dropping probability comparison.