ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 2, Issue 11, November 2013

Offset Time Management For Fairness Improvement And Blocking Probability Reduction In Optical Burst Switched Networks

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Abstract*— This paper pays a great attention to the process of calculating the burst offset time in Wavelength Division Multiplexed (WDM) Optical Burst Switching (OBS) networks. The blocking probability of the burst in the case of using variable offset time is studied through theoretical analysis. The analysis is based on the first-passage-time distributions. In order to perform offset time management, two algorithms have been used to determine the optimum offset values in order to guarantee an objective blocking probability value. Of course, the optimum offset values obtained greatly solve the fairness problem. As a result, for all ingress-egress node pairs in an OBS network, bursts with different hop lengths have equal likelihood to get through. The results for three cases are presented.

Index Terms*— Optical Burst Switching; Fairness; Blocking Probability; Offset Time Management.

1. Introduction

Optical Burst Switching (OBS) achieves, to a certain extent, a balance between the coarse-grained circuit switching and fine-grained packet switching, and combines the best of both paradigms while avoiding their shortcomings [1—5]. The main motivation for considering OBS is that some traffic in broadband multimedia services is inherently bursty. More specifically, traffic generated by web browsers, wide-area Transmission Control Protocol (TCP), and variable bit rate video sources are all self-similar (or bursty at all time scales) [1]. Therefore, bursty traffic results from multiplexing a large number of self-similar traffic streams [6]. Also, OBS can provide high bandwidth transport services at the optical layer for bursty traffic in a flexible, efficient as well as feasible way.

In OBS networks, client data is aggregated at the network ingress and sent as bursts across the network. For each burst, a reservation control packet is sent on a dedicated control wavelength channel prior to sending the burst on one of the data wavelength channels after a prespecified offset time. Hence, there is an offset time between the control packet and the corresponding burst.

This means that OBS includes a separation between the control plane and the data plane. The control packet is used to configure intermediate OBS nodes along the path between the ingress node and egress node of the OBS network. The offset time is set such that the burst can be all-optically switched at intermediate nodes in a cut-through manner [7]. As a consequence, the burst does not need to be Optical-Electrical-Optical (OEO) converted, buffered, and processed at intermediate nodes, thus avoiding the need for optical Random Access Memory (RAM) and Fiber Delay Line (FDL), as opposed to Optical Packet Switching (OPS) networks. Moreover, OBS networks allow for statistical switching at the burst-level granularity. Also, by controlling the offset time, service differentiation and various Quality-of-Services (QoS) levels can be achieved [7].

In OBS, the wavelength on a link used by the burst will be released as soon as the burst passes through the link, either automatically according to the reservation mode as in Just-Enough-Time (JET) or by an explicit release packet. Also, several signaling protocols have been proposed for OBS [8, 9]. In a Tell-And-Go (TAG) based OBS protocol, a burst is sent by the source along with the control packet without any offset time. In addition, at each subsequent intermediate node, the burst waits for the control packet to be processed. Accordingly, the minimum latency of the burst including the total propagation time, denoted by D, but excluding its transmission time, is D + Δ.H, where Δ is the time to process the control packet, and H is the number of hops along the path. In JET, we can choose the offset time to be Δ.H, to ensure that there is enough time for each node to complete the processing of the control packet before the burst arrives [1]. In this way, the burst will not encounter a longer latency than using TAG based OBS protocols. Therefore, in this paper, we focus on JET, in our analysis and calculations, as a signaling protocol in which the offset time plays an important role.

At the OBS Medium Access Control (MAC) layer, source and destination OBS users located at the edge of the OBS network perform the functions of burst assembly/disassembly, offset computation, control packet generation, routing and wavelength assignment (RWA), and signaling as shown in Fig. 1. At the optical layer, intermediate core OBS nodes perform the functions of scheduling and contention resolution of in-transit bursts. Both the OBS MAC layer and the underlying optical layer offer services that guarantee certain burst blocking probabilities to the higher layers [7, 10].

In some recent papers, a signaling protocol called Just-In-Time (JIT) is used in the analysis. But, here we study the effect of using variable offset time on the network performance. Therefore, we use JET instead of JIT because in JIT, intermediate OBS nodes do not take the offset time information carried in control packets into account. An OBS node configures its optical switches for the incoming burst immediately after receiving and processing the corresponding control packet. This leads to an increased burst loss probability. On the contrary, JET signaling depends on the offset time information carried in each control packet. Therefore, higher wavelength utilization can be achieved by enabling OBS nodes to make delayed reservation for incoming bursts [7]. With delayed reservation, the optical switches at a given OBS node are configured right before the expected arrival time of the burst. Strictly speaking, the major difference between JET signaling and JIT signaling is the time when optical switches are configured at OBS nodes. Another important feature of JET signaling is that the burst length information carried in the preceding control packet is used to enable close-ended reservation. Therefore, explicit release of the configured resources is not required. The close-ended reservation helps OBS nodes make intelligent decisions about whether it is possible to schedule another newly arriving burst. As a result, JET signaling is able to outperform JIT signaling in terms of bandwidth utilization and burst loss probability, at the expense of increased computational complexity [7, 11].

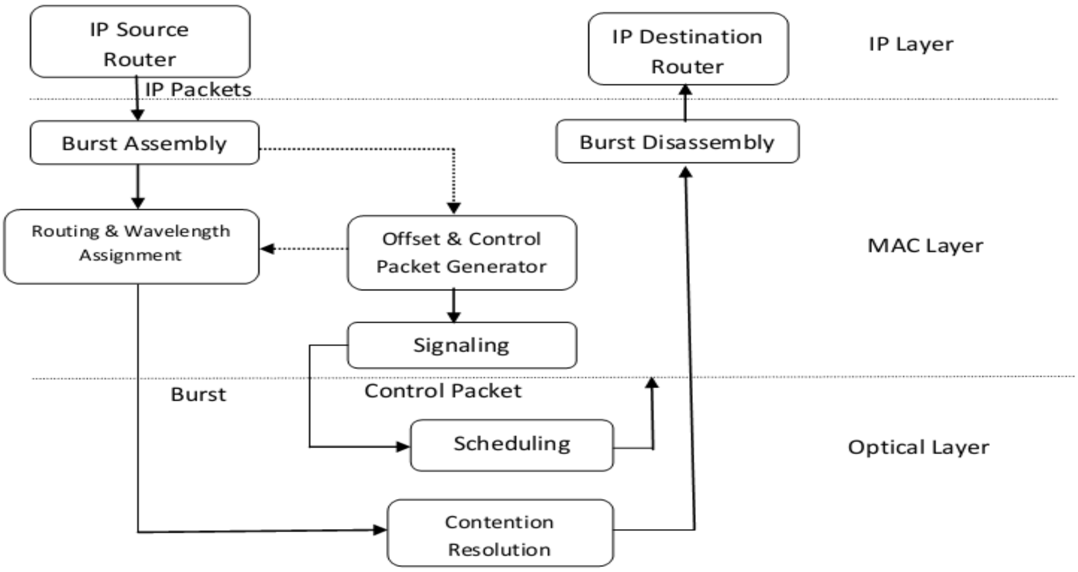

Fig.1. Block diagram of OBS networks consisting of IP, MAC, and optical layers.

Contention resolution is one of the main design objectives in OBS networks. Contention occurs if a burst arrives at an OBS node and all local resources are occupied or if two or more simultaneously arriving bursts contend for the same resource [7]. Determining the blocking probability for data bursts in an OBS network depends on the signaling protocol used in that network [12]. Also, at [13], the effect of the burst offset time on the burst blocking probability is studied. Results show that as the offset time value increases, the blocking probability decreases. Another observation is that the blocking probability increases with the offered load. But, this result is intuitive. In this paper, an optimization is made to calculate the optimum offset time that is needed to achieve smallest blocking probability. Several techniques have been proposed, such as in [14], to provide different levels of Quality-of-Service (QoS). The key idea is to increase the offset time for high priority bursts than those of lower priority. In this paper, we show the effect of using variable offset time and compare it with constant one. Our results show the great contribution of the variable offset time to reduce the burst blocking probability. Also, we use two techniques in [13, 15] to manage the offset time in order to improve the fairness between bursts, having different hop lengths, to be equally subjected to the same blocking probability conditions, as will be explained further in this paper. The rest of the paper is organized as follows. In Section II, we show the effect of the offset time on the blocking probability. In Section III, a comparison between constant and variable offset time is presented, followed by the calculation of the blocking probability in Section IV. Section V is devoted to the management of the offset time. Concluding remarks are given in Section VI.

2. Effect Of The Offset Time On The Burst Blocking Probability

In this section, we show the effect of the burst offset time on the burst blocking probability. Consider the offset time has a uniform distribution over [0, t_{max}] slots. The maximum offset time t_{max} is arbitrary chosen to be 20 time slots. This is based on the slotted timing model of OBS networks. By using standard values for burst length and maximum offset values, each time slot is corresponding to 9 μsec. In [12], three values of the offset time are taken into account. As stated earlier, as the offset time increases, the blocking probability decreases. As a consequence, the following relation is valid; (PB(0.2 t_{max}) > PB(0.5 t_{max}) > PB(t_{max})). This behavior is expected because as the offset time increases, the contended bursts with the current burst decrease. The process of determining the optimum offset time needed to achieve reasonable performance is not a trivial issue. It can be explained by noting that longer offset values increase the end-to-end delay and require large buffers at the ingress nodes to queue the bursts. Also, shorter offset values require Switch Control Units (SCU) with high processing speed, and this requires more power. Therefore, we propose an optimum values of the offset time required to guarantee prespecified performance for a wide range of traffic load.

2. 1. Constant Versus Variable Offset Time

In this section, we present the motivation towards variable offset time instead of constant one. In the case of constant offset time, we use the formula of the burst loss probability which is equal to $1-(1-\rho)^H$ where ρ is the offered load. For ρ=0.1 and H=5, this probability equals 0.409 i.e. more than 40% of the bursts will be lost. Furthermore, there is no way to decrease the blocking probability below than that value [12]. Therefore, the constant offset time doesn't achieve the objective blocking probability value.

Figure 2 shows the great difference in the blocking probability between the variable and constant offset times. The burst blocking probability is calculated with number of hops H=5. Depending on the results obtained in [16], and by fitting the values of P_B on ρ yields:

$$P_B = 0.36458\rho^3 - 0.83044\rho^2 + 0.96369\rho + 0.0003043 \quad (1)$$

From the regression analysis, the norm of residuals equals 0.0011787. Expected trend of the curve can be noticed. Indeed, the blocking probability increases as the offered load increases. However, at a specific value of the offered load, the blocking probability in the case of variable offset time is lower than its counterpart when using constant offset time. Of course, as ρ increases, the system complexity and cost increase as well. Also, this great enhancement of the blocking probability, in the case of variable offset time, is at the expense of larger delay and requires larger buffers at the ingress nodes.

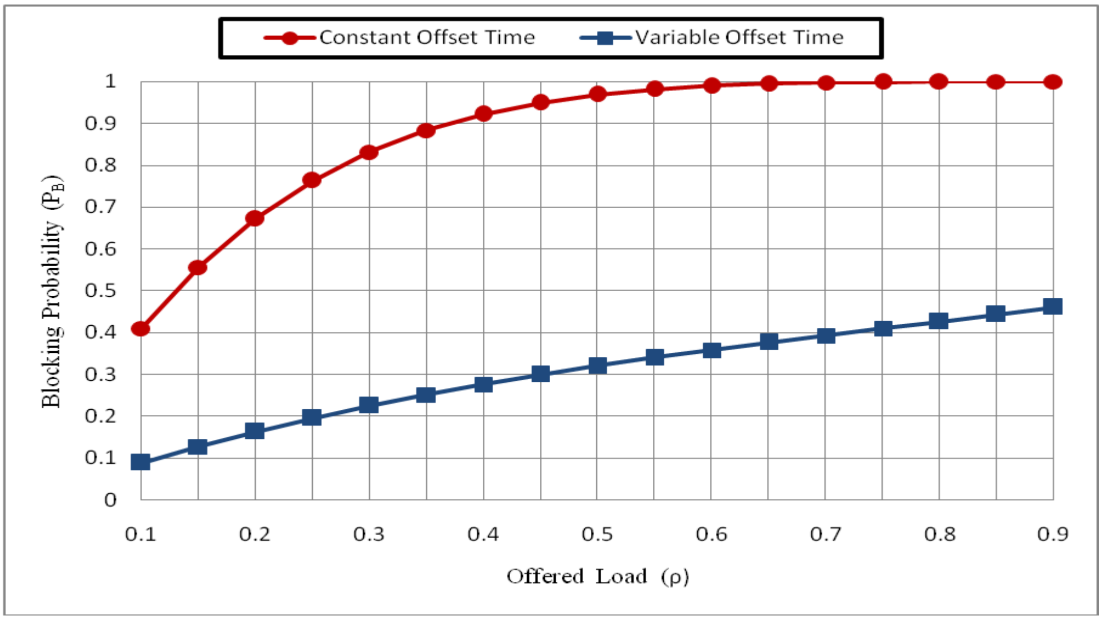

Fig. 2. Blocking probability versus offered load for constant and variable offset time.

2. 2. Blocking Probability Calculation

2. 2. 1. Blocking Probability In Terms Of The First-Passage-Time Distributions

The signaling protocol used in an OBS network is important for determining the burst blocking probability. For JIT protocol, the blocking probability at a node can be calculated by using the Erlang's B-formula for the loss probability:

$$P_B = \frac{\rho^k / k!}{\sum_{i=0}^{k} \rho^i / i!} \quad (2)$$

In this equation, k is the number of wavelengths, and ρ is the offered load. For JIT protocol, the offered load is λ(b + t), where λ is the mean arrival rate, b is the burst duration in time units, and t is the burst offset time in time units. This formula is based on the concept of the JIT signaling protocol, in which the reservation is made after receiving and processing the preceding control packet at each core node. Therefore, each request blocks the channel for the duration of the sum of the burst time and the offset time [11]. Only the offered load is changed when calculating the blocking probability in the case of JET protocol. The reservation is made just before the arrival time of the burst. Therefore, the offered load is λb [11, 17]. Of course, this approximation simplifies the problem by neglecting the effect of both the offset time and the burst length on the blocking probability. This can be explained by noting that Erlang's B-formula calculates the probability that a channel will be free on the arrival of a burst. The issue that the channel remains free for the service duration i.e. the length of the burst is not considered. As a consequence, Erlang's B-formula cannot be considered as a good approximation for the blocking probability because it fails to capture the effects of neither the offset time nor the burst length. A comparison between the results obtained from Erlang's B-formula and from our approximation will be illustrated further in this paper. The blocking probability can be expressed in terms of the first-passage-time distributions [18]. Also, as stated in [12], and noting that the output link, which carries K wavelength channels, can be modeled as a non-homogenous Markov chain with transitional probability matrix $Q^{(i)}$;

$$Q^{(i)} = \begin{bmatrix} q_{0,0}^{(i)} & q_{0,1}^{(i)} & \cdots & q_{0,k}^{(i)} \\ q_{1,0}^{(i)} & q_{1,1}^{(i)} & \cdots & q_{1,k}^{(i)} \\ \vdots & \vdots & \ddots & \vdots \\ q_{k,0}^{(i)} & q_{k,1}^{(i)} & \cdots & q_{k,k}^{(i)} \end{bmatrix} \quad (3)$$

Same assumptions as the model developed in [12] can be used. We assume that the offset time t and the burst length b are integer multiples of time slot units. We use i to indicate the slot number. Also, arrivals and departures occur at slot boundaries. Let $N^{(i)}$ represents the number of channels reserved on the output link in slot i ($N^{(i)} = 0,1,\dots\dots,k$).

Also, the probability distribution of $N^{(i)}$:

$$R_n^{(i)} = P(N^{(i)} = n), \qquad n=0,1,\dots\dots\dots,k \qquad (4)$$

The blocking probability can be expressed in terms of the first-passage-time distributions [12]:

$$P_B(t,b) = 1 - \left[F_0(t,b) \sum_{n=0}^{k-1} R_n^{(j)} \right] \qquad (5)$$

This equation can be explained as follows. A reservation request for a unit length data burst with offset time equal to j slots will be blocked with probability $R_k^{(j)}$. Therefore, eq. 5 says that the probability the reservation request will be accepted is equal to probability that at least one wavelength will be free at the arrival time of the data burst, and will remain free for the duration of the data burst. The probability $R_n^{(j)}$ can be calculated as:

$$R_n^{(j)} = \Pi\, Q^{(0)} Q^{(1)} \dots\dots\dots Q^{(j-2)} Q_{(:,n)}^{(j-1)} \qquad (6)$$

where the symbol $Q_{(:,n)}^{(j-1)}$ denotes the n^th^ column of the matrix $Q^{(j-1)}$. The probability that the wavelength will be free for the duration of the data burst can be expressed as:

$$F_0(t,b) = e^{-\lambda_s (b-1)\left[1 - C(t+b/2)\right]} \qquad (7)$$

where λ_s is the arrival rate for a single wavelength channel, and equals λ/k, λ is the total arrival rate, b represents the burst length in terms of no. of slots, t is the burst offset time, $C = \frac{1}{1+t_{\max}}$; t_{max} is the maximum offset time which is chosen to be 20 time slots ≅ 180 µsec. As mentioned earlier, and it is cleared from the previous equations, the offset time has an effect on the blocking probability.

2. 2. 2. Blocking Probability In The Case Of Variable Offset Time

In this section, we present a closed form of the blocking probability that includes the variable offset time. The variation of the offset time here is due to variable Burst Control Packets (BCPs) sojourn times. This is also assumed in [13] that the Switch Control Units (SCUs) don't operate at the peak rate. Therefore, some BCPs have to wait in a queue to be processed, and then the BCP sojourn time will be variable. If we assume that there are M identical SCUs along the burst path, then the waiting time distribution $F_Y(y) = P(Y \le y)$ with load ρ and unity service time is:

$$F_Y(y) = (1-\rho)^M \times \sum_{i=0}^{[y]} \sum_{j=0}^{M-1} \frac{(-1)^j}{i! \times j!} \times \binom{M+i-1}{i+j} \times [\rho(i-y)]^{i+j} \times e^{-\rho(i-y)} \qquad (8)$$

where Y is the random variable which indicates the waiting time for M SCUs along the burst path, and equals $\sum_{i=1}^{M} T_i$, T_i is the waiting time at i^th^ SCU. This waiting time can be variable either due to queuing delay or variable service time or both. Here, we use constant service time (unity) and variable queuing delay as assumed in [13]. Applying the central-limit theorem, and without loss of generality, the total waiting time (Y) tends to be a Gaussian distribution [19]. For M SCUs from source to destination and load ρ, the offset time is:

$$t = M + \frac{1-P_B}{F_Y(y)} \qquad (9)$$

where $F_Y(y)$ is given by (8) and P_B is the burst blocking probability. Substituting from eq. (9) into (7) yields:

$$F_0(t,b) = e^{-\lambda_s (b-1)\left[1 - C(M + \frac{1-P_B}{F_Y(y)} + \frac{b}{2})\right]} \qquad (10)$$

substituting into eq. (5) and after some algebraic manipulations:

$$\sum_{n=0}^{k-1} R_n^{(j)} \times \exp\{-\lambda_s (b-1)[1 - C(M + \frac{1-P_B}{F_Y(y)} + \frac{b}{2})]\} + P_B = 1 \qquad (11)$$

This equation for calculating the blocking probability, in the case of variable offset time, can be solved either by using Matlab program or by using the Lambert W function [20]. The Lambert W function can be used to solve various equations involving exponentials and also occurs in the solution of delay differential equations. If $y=xe^x$ then x=W(y), where W is the Lambert W function. An example is given in Appendix I. A comparison between the results obtained from Erlang's B-formula in eq. (2) and results from our approximation in eq. (11) is performed. Figs. (3—6) confirm that our approximation is more accurate than Erlang's loss formula. In addition, the curve obtained from our approximation follow the same trend as the Erlang's loss formula, thus providing strong evidence on the accuracy of our analysis. It is important to state again that Erlang's loss formula doesn't take the effect of neither the burst length nor the offset time into account. It is also shown that the difference between our approximation and Erlang's loss formula tends to decrease as the offered load decreases.

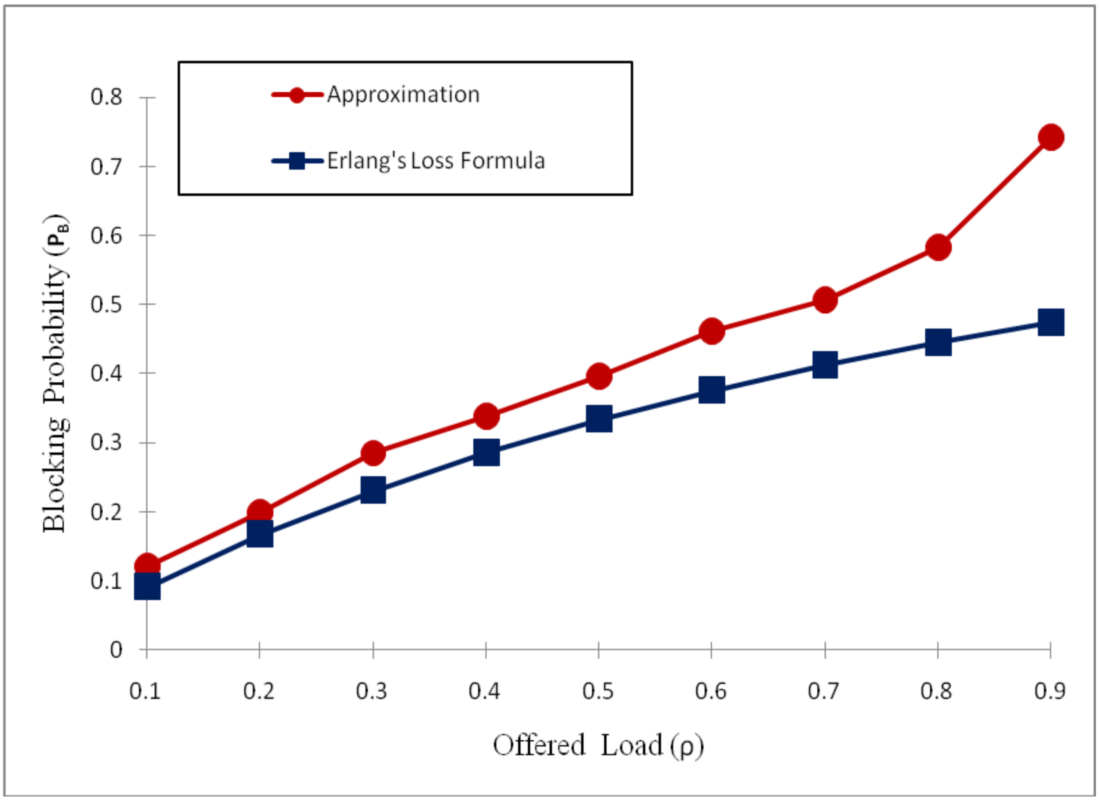

Fig. 3. Proposed approximation vs. Erlang's loss formula (k=1).

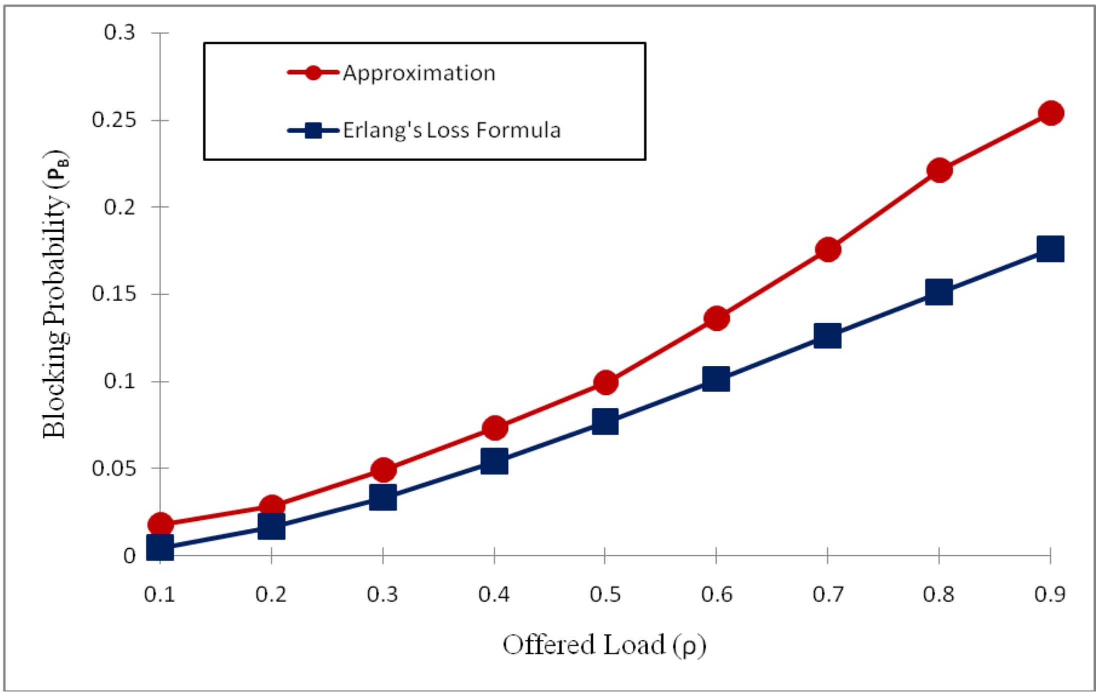

Fig. 4. Proposed approximation vs. Erlang's loss formula (k=2).

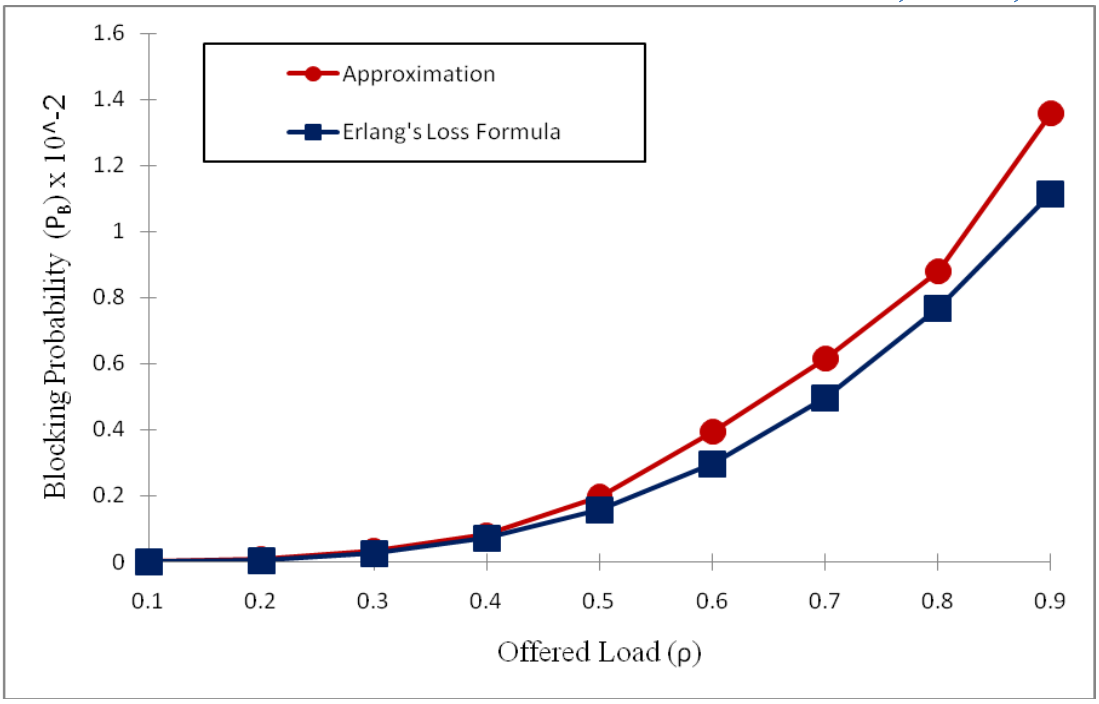

Fig. 5. Proposed approximation vs. Erlang's loss formula (k=4).

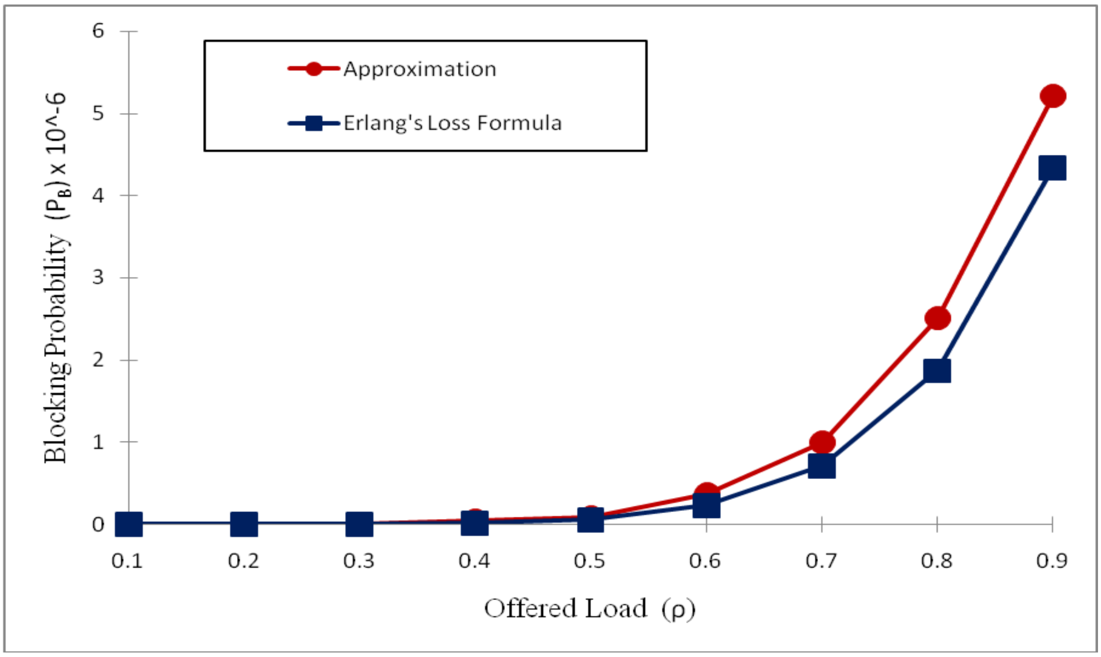

Fig. 6. Proposed approximation vs. Erlang's loss formula (k=8).

3. 3. Offset Time Management

3. 3. 1. Offset Time Calculation Based On LOT Algorithm

In this section, we present the 1st method for managing the offset time. This technique, named Load-adaptive Offset Time algorithm (LOT), is proposed in [13] and the variation of the offset time here is based on the variable BCPs sojourn times i.e. adaptive to the SCUs load. Based on LOT algorithm, we calculate the offset time that guarantees a drop probability equal to P_B. Here, 5 SCUs are assumed. Depending on the results obtained in [13], and by fitting the values of t on P_B in the case of ρ=0.1 yields:

$$t = -781.25P_B^3 + 140.63P_B^2 - 17.768P_B + 55.371 (\mu sec) \quad (12)$$

From the regression analysis, the norm of residuals equals 0.085042. On the same manner, in the case of ρ=0.7:

$$t = 1.06\times10^6 P_B^4 - 6.1\times10^5 P_B^3 + 1.37\times10^5 P_B^2 - 1.354\times10^4 P_B + 633.81 (\mu sec) \quad (13)$$

From the regression analysis, the norm of residuals equals 0.48616. Figs. 7 & 8 show that larger offset times are required to achieve lower values of blocking probability. This is due to the fact that as the offset time increases, the contended bursts with the current burst decrease. In the case of ρ=0.7, blocking probability values below 0.07 cannot be achieved because the required offset time will exceed the maximum allowable standard values (180 μsec). This maximum value is chosen in order not to cause higher end-to-end delay and also not to require large buffers at the ingress node.

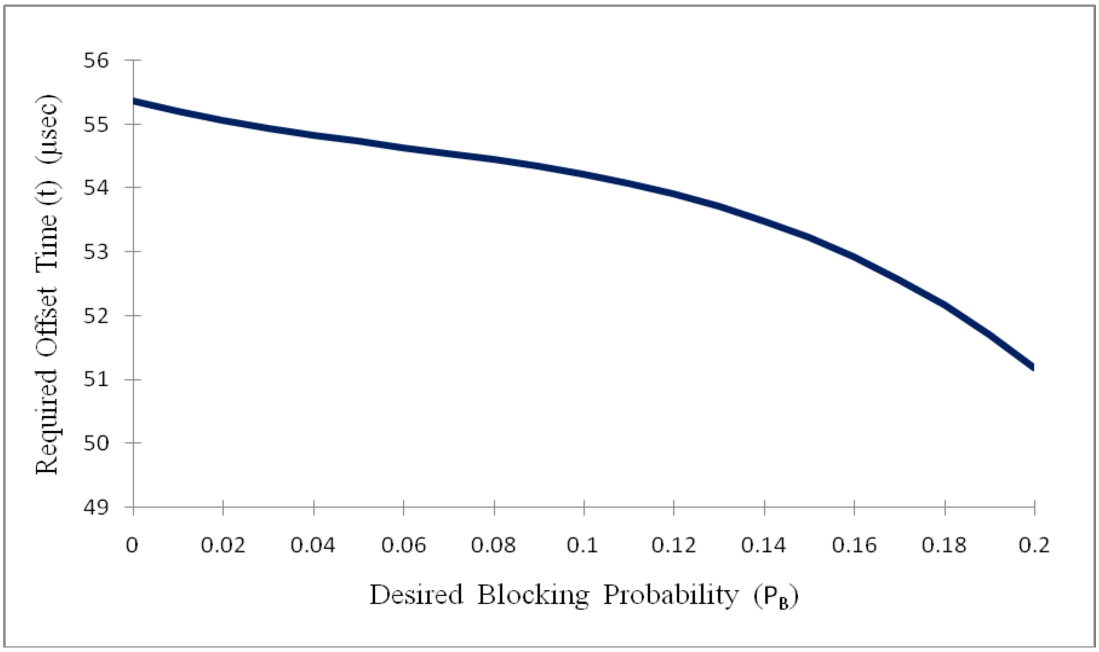

Fig. 7. Offset values required to achieve desired blocking probability for ρ=0.1

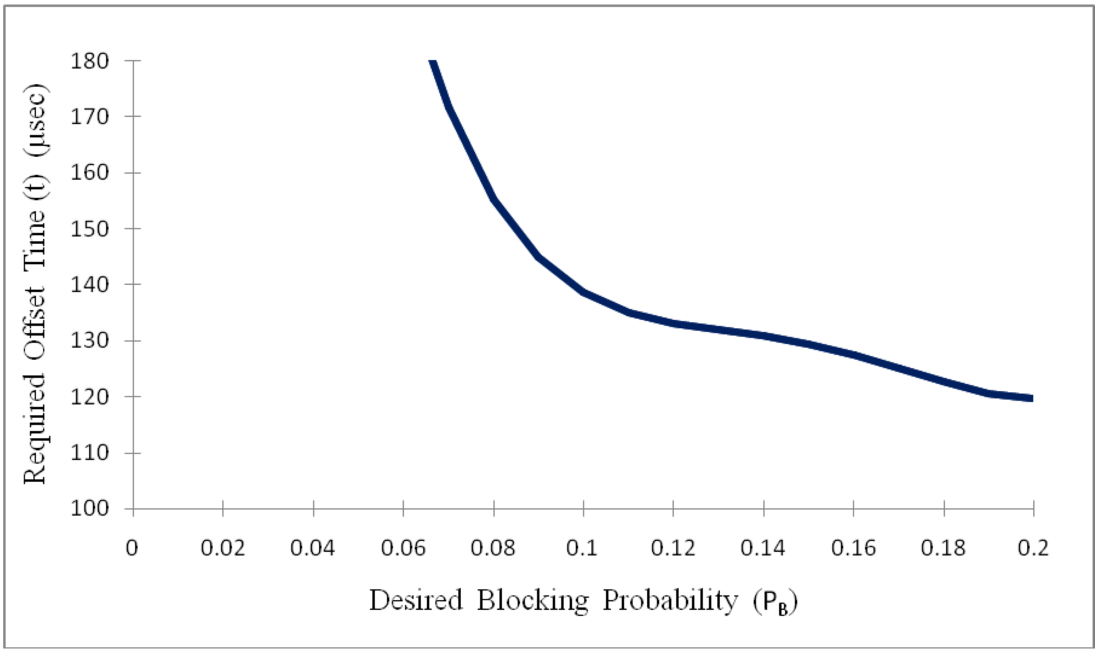

Fig. 8. Offset values required to achieve desired blocking probability for ρ=0.7

Depending on the results obtained in [13], and by fitting the values of t on ρ in the case of P_B=0.1 yields:

$$t = 1.6\times10^5\rho^5 - 2.6\times10^3\rho^4 + 1.5\times10^3\rho^3 - 4.1\times10^2\rho^2 + 45\rho + 52 \quad (\mu sec) \quad (14)$$

From the regression analysis, the norm of residuals equals 0.7358. On the same manner, in the case of P_B=0.2:

$$t = 1.4\times10^3\rho^5 - 2.3\times10^3\rho^4 + 1.4\times10^3\rho^3 - 3.6\times10^2\rho^2 + 40\rho + 51 \quad (\mu sec) \quad (15)$$

From the regression analysis, the norm of residuals equals 0.65404. Fig. 9 shows the offset time values against the offered load for two objective values of the blocking probability (P_B=0.1&0.2). Higher values of burst blocking probability i.e. larger than 0.2 are not interesting to consider in our calculations since they don't represent a good performance. Fig. 9 confirms that offset values required to guarantee P_B=0.1 are larger than their counterparts which are required for P_B=0.2. For very high traffic loads (>0.7), the two objective values of the blocking probability (0.1&0.2) cannot be achieved with allowable offset values (0—180μsec). This is consistent with previous results in this paper.

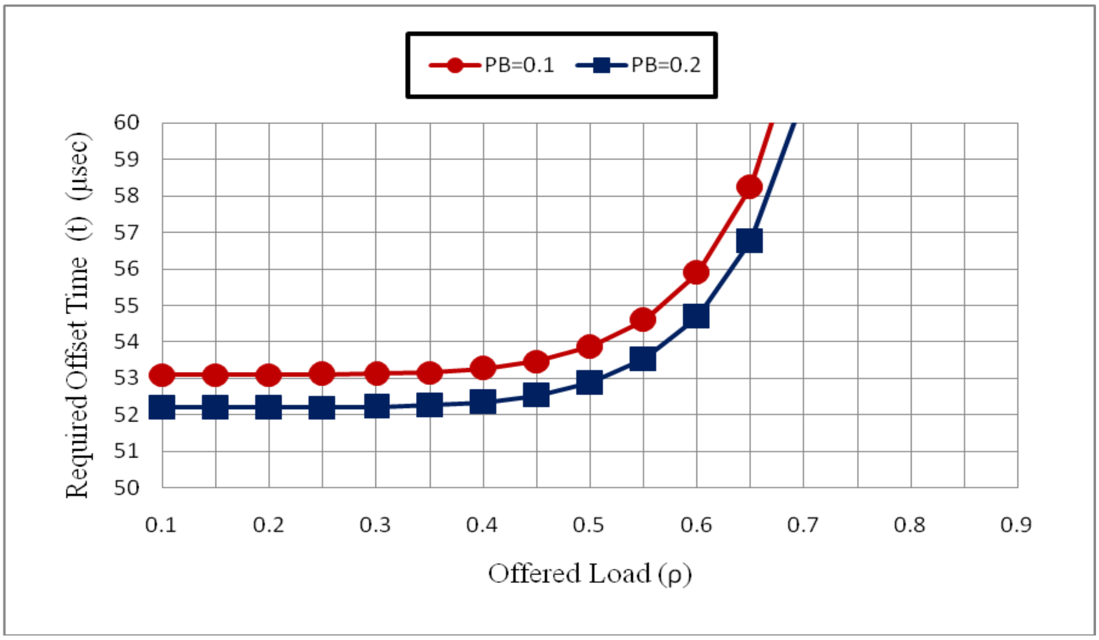

Fig. 9. Offset values vs. offered load. These offset values are required to guarantee blocking probability of 0.1 and 0.2.

3. 3. 2. Offset Time Calculation Based On LSOS Algorithm

An important aspect of QoS support in OBS networks is fairness. Therefore, we choose an efficient fairness method as the 2nd method for managing the offset time in OBS networks. This algorithm is called Link Scheduling state based Offset Selection (LSOS) [15]. Naturally, bursts that traverse longer paths are more likely to be dropped compared to burst that traverse shorter paths resulting in a fairness problem. The objective of LSOS is to manage the offset times and choose them based on the link states for bursts with different hop lengths such that they perform almost equally. The link scheduling probabilities are computed at the core nodes and collected periodically from core nodes by the edge nodes which then determine the offset times needed for bursts traversing different hop lengths. The basic assumption is that link states normally don't change abruptly [15]. To illustrate the used algorithm, consider 2-hop path with the link scheduling probabilities for the links 1—2 and 2—3 for different offset time values are depicted in the following table 1. To achieve fairness, a burst that traverses 2-hops should suffer from the same blocking probability as if it traverses only one hop. Simply, a reference probability value is determined by the scheduling probability for one hop path which corresponds to the minimum required initial offset time. It can be observed from table 2 that an offset value of 72 μsec gives the path scheduling probability which is the closet to the reference probability value. Therefore, this algorithm chooses 72 μsec as the initial offset time for bursts that traverse these 2-hops.

Table 1. offset with link states at first and second node.

Offset (μsec) with link states at 1st node	Link Scheduling Probability	Offset (μsec) with link states at 2nd node	Link Scheduling Probability
18	0.9681	18	0.9581
27	0.9783	27	0.9634
36	0.9805	36	0.9757
45	0.9824	45	0.9770
54	0.9837	54	0.9779
63	0.9846	63	0.9860
72	0.9850	72	0.9879
81	0.9902	81	0.9891

Table 2. Path scheduling probability for 2-hop path for different offset values.

Offset at 1st node (µsec)	Offset at 2nd node (µsec)	Path Scheduling Probability
36	18	0.9805 × 0.9581 = 0.9394
45	27	0.9824 × 0.9634 = 0.9464
54	36	0.9837 × 0.9757 = 0.9598
63	45	0.9846 × 0.9770 = 0.9620
72	54	0.9850 × 0.9779 = 0.9632
81	63	0.9902 × 0.9860 = 0.9763

The computation process of the link scheduling probabilities is deeply explained in section 3 in [15]. On the same manner, as shown in Fig. 10, we present a 6-hop path example to calculate the optimum offset time needed to ensure fairness. This means that no. of SCUs is 5, as assumed earlier. Three cases are included as follows.

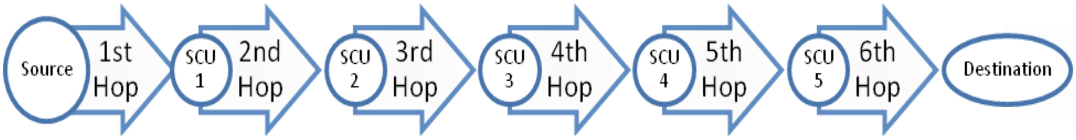

Fig. 10. 6-Hop path example for managing offset time using LSOS.

First case: A-LSOS

Here, all the links states are taken into account for advertisement overheads. Fig. 11 illustrates the optimum offset values for bursts that transverse 6-hops in order to suffer from the same blocking probability as the bursts that transverse only one hop.

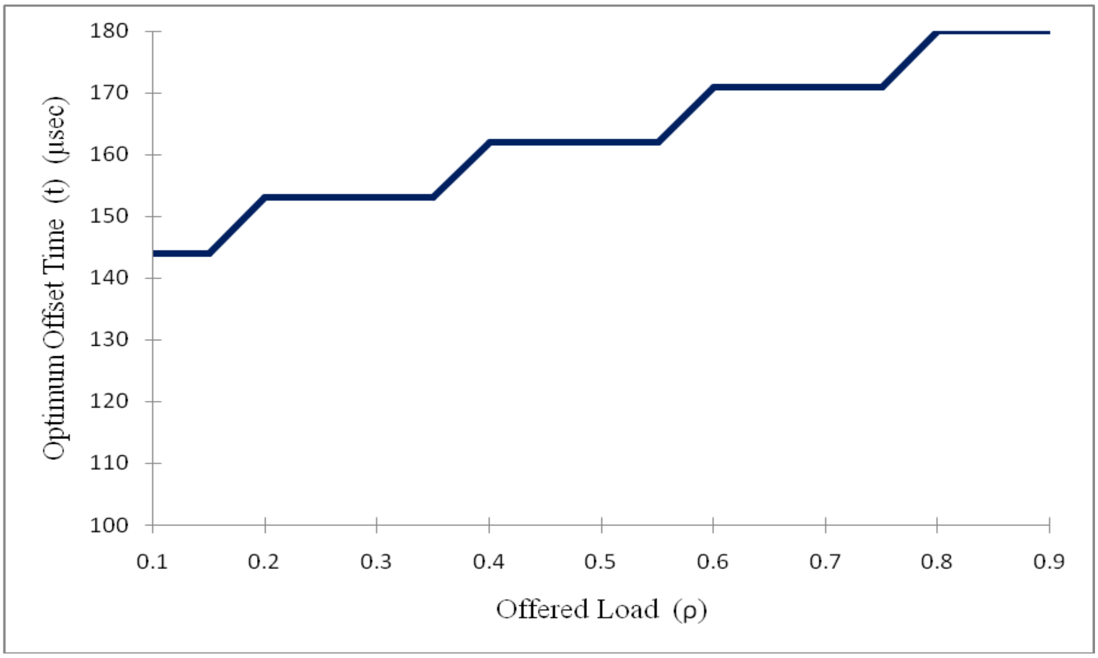

Fig. 11. Optimum offset time for bursts that transverse 6-hops vs. offered load in the case of A-LSOS.

Second case: 3-LSOS

In order to reduce link state advertisement overheads, link states on only 3-links can be collected and extrapolated to the remaining links along the route. In this case, we take only 1st 3-links into account instead of all 6-links. We choose the bottleneck link i.e. the link with the smallest scheduling probability. We can deduce from Fig. 12 that the optimum offset time is smaller than the case of A-LSOS since here we don't take all the network state into account.

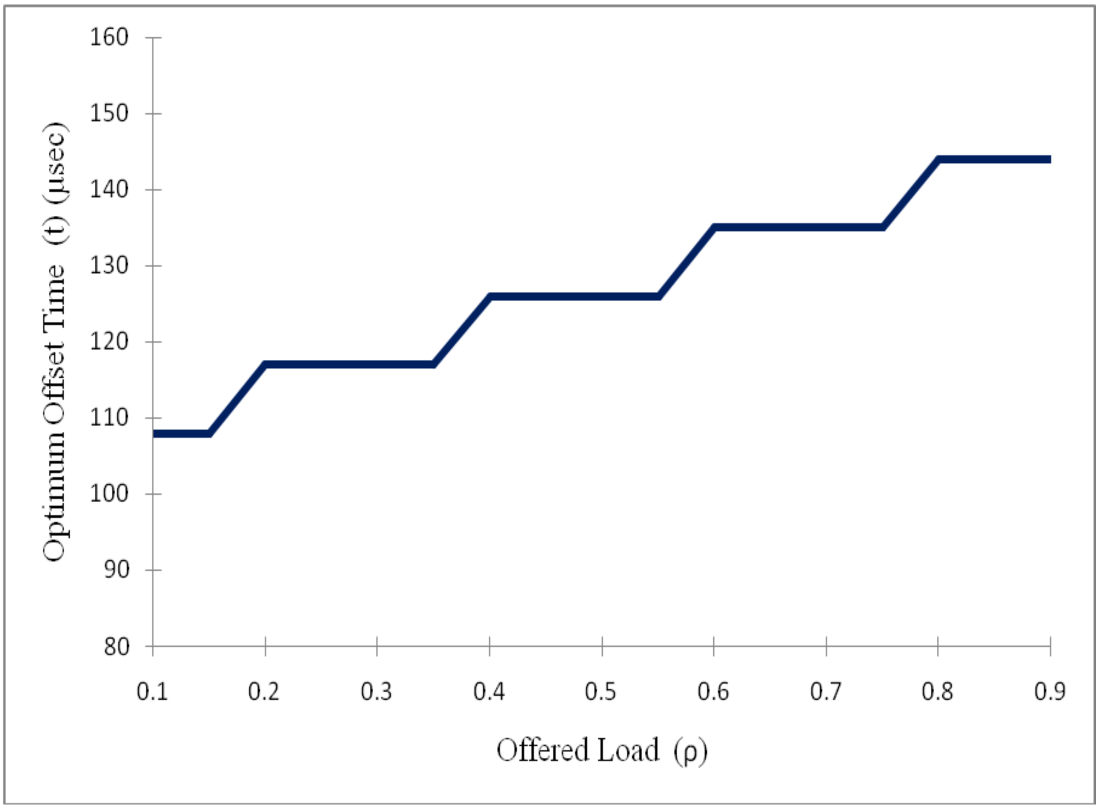

Fig. 12. Optimum offset time for bursts that transverse 6-hops vs. offered load in the case of 3-LSOS.

Third case: 1-LSOS

To further reduce the amount of link states needed, only the link state of the 1st link is used. Therefore, this case is denoted 1-LSOS. Accordingly, the optimum offset time appearing in Fig. 13 is much smaller than before.

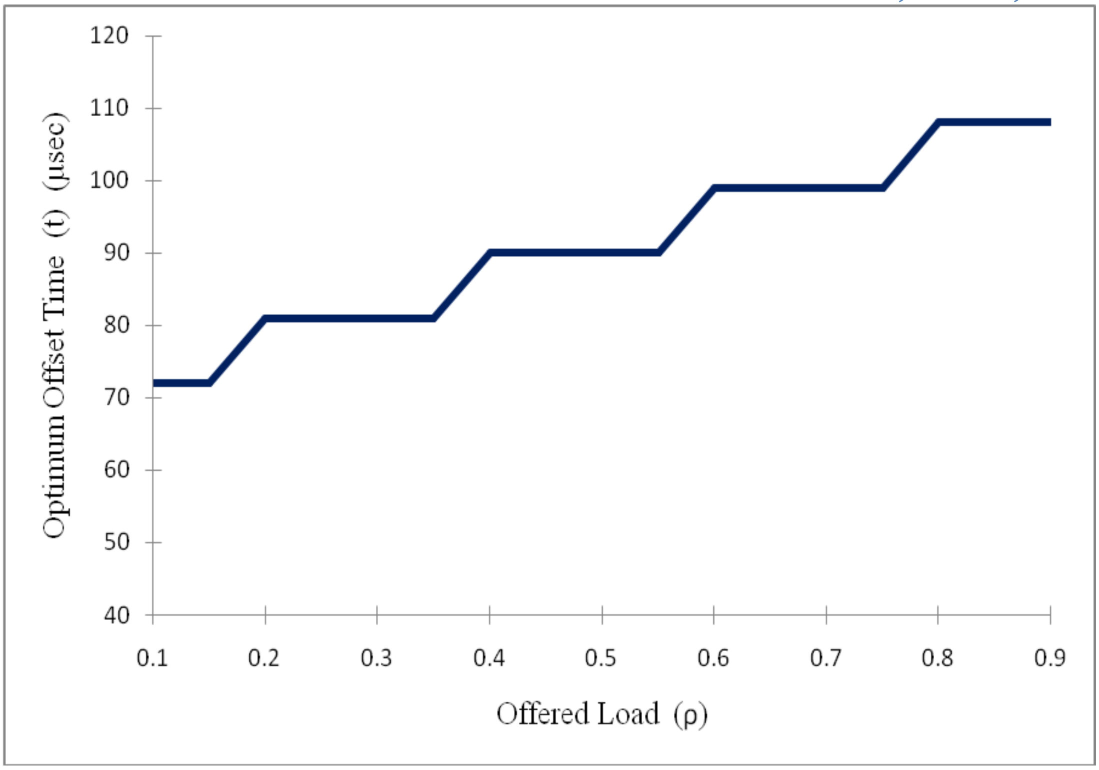

Fig. 13. Optimum offset time for bursts that transverse 6-hops vs. offered load in the case of 1-LSOS.

4. CONCLUSION

In a summary, a great attention has been paid to the delayed reservation techniques that reveal the importance of using burst offset time while other immediately reservation techniques have been neglected. We have studied the effect of the burst offset time on the blocking probability. It can be indicated that as the offset time increases, the blocking probability decreases. A comparison between constant and variable offset times has been presented. From our results, the blocking probability has been much reduced by using variable offset time instead of constant one.

A closed form for calculating the blocking probability in the case of variable offset time has been proposed. We have showed the effectiveness and feasibility of our approximation over Erlang's formula since we take the burst length and the offset time effects into account during the calculation of the burst blocking probability.

Two algorithms for offset time management have been presented. In LOT, the required offset value that achieves a desired blocking probability has been calculated. Also, we have calculated the required offset times that guarantee two objective values of blocking probability (P=0.1&0.2) for different traffic loads. In LSOS, 3-cases have been presented. Improvement in fairness is achieved with a predefined range of offset times.

5. APPENDIX I

In this appendix, we show an example on solving exponential equations using Lambert W function.

For $2^t = 5t$, calculate t.

$$1 = 5t \times 2^{-t} \qquad \therefore \ln\left(\frac{1}{5t}\right) = -t\ln 2$$

$$\therefore \frac{1}{5t} = e^{-t\ln 2}$$

$$\frac{-1}{5} = -t \times e^{-t\ln 2} \quad \therefore \frac{-\ln 2}{5} = -t\ln 2 \times e^{-t\ln 2}$$

$$\therefore -t\ln 2 = W\left(\frac{-\ln 2}{5}\right)$$

$$\therefore t = \frac{-W\left(\frac{-\ln 2}{5}\right)}{\ln 2} = 0.2355$$

Generally, if $p^{(at+b)} - ct - d = zero$

$$\therefore t = \frac{-W\left(\frac{-a\ln p}{c} \times p^{b-\frac{ad}{c}}\right)}{a\ln p} - \frac{d}{c}$$

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