An Enhanced Mathematical Model for Performance Evaluation of Optical Burst Switched Networks

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ABSTRACT

An enhanced mathematical model is introduced to study and evaluate the performance of a core node in an optical burst switched network. In the proposed model, the exact Poisson traffic arrivals to the OBS node is approximated by assuming that the maximum allowed number of arrivals to the OBS node, in a given time slot, is two (instead of infinity). A detailed state diagram is outlined to illustrate the problem, and then a mathematical model based on the equilibrium point analysis (EPA) technique is presented. The steady-state system throughput is derived from the model which is built in the absence of wavelength conversion capability. Our proposed model is aided by a simulation work which studies the performance of an OBS core node under the assumption of Poisson traffic arrivals (the exact case) and calculates the steady-state system throughput. The results obtained from the proposed mathematical model are consistent with that of simulation when assuming Poisson traffic arrivals and this consistency holds for a wide range of traffic load.

Keywords: Optical Burst Switching (OBS), Optical Circuit Switching (OCS), Optical Packet Switching (OPS), Just-In-Time (JIT), Just-Enough-Time (JET).

I. INTRODUCTION

Optical Burst Switching (OBS) is a new switching paradigm that can support bursty traffic introduced by upper layer protocols or high end user applications. OBS can be considered as the gate through which the envisaged world of optical internet will be conquered by implementing IP software directly over WDM optical layer (IP/WDM).

The idea of burst switching, first proposed by researchers in [1], emerges to combine the best of both OCS and OPS. The burst is the basic switching unit in OBS networks. The variability in the burst length from being as short as a packet to being as long as a session puts OBS as an intermediate solution between OCS and OPS. Previous work carried out in OBS performance evaluation either used simulation or simply adopted the M/M/k/k model [5]. This paper introduces an enhanced mathematical model based on EPA analysis to measure the performance of an OBS network.

The data carried in the burst results from the aggregation process of many packets (e.g. IP packets) carried out by an assembly node at the edge of the OBS network. After being assembled at edge nodes (called ingress nodes), the data bursts go through the core network which consists of core nodes which has the function of forwarding the data bursts (without going back to the electronic domain) until reaching their destination edge nodes (called egress nodes). Egress nodes then disassemble burst back into packets, each of them to go to its destination.

Generally, the main idea beyond all OBS protocols is the separation of the header (carrying the control information) and the payload (carrying the data). Thus, the control packet (header) will be on a separate channel, called the control channel, while the burst (payload) remains on the data channel.

In this paper, the focus is on studying the performance of an OBS core node using either the JIT protocol or the JET protocol in the reservation mechanism. Both protocols are considered as one-way reservation protocols. The main difference between JIT and JET is that the former implies an immediate reservation strategy while the latter adopts a delayed reservation policy. Briefly, the control packet in JIT protocol is sent prior to the data burst by some offset time to reserve sufficient bandwidth immediately after the processing of the control packet at the core node and configure the switching fabric to route the upcoming data burst to the destined output port.

JET is a more efficient protocol where the control packet contains information about the offset time and the bandwidth reservation is done just before the data burst reaches the node, i.e. the reservation is delayed till the data burst reaches the node. Another difference between JIT and JET is in the release mechanism of the reserved bandwidth. In JIT, there is a release packet that is sent explicitly to release the reserved bandwidth, while in JET; the control packet contains information about the burst length to allow the core node to release the reserved bandwidth implicitly after the burst departs the node. In both protocols, the data burst waits at the ingress node in an electronic buffer for an offset time equivalent to the total time needed by the control packet to be processed at each node. Fig.1 and Fig.2 illustrate both JIT and JET respectively.

To make the proposed model valid to be used for both JIT and JET protocols, it is obligatory to compensate for the difference between the two reservation schemes applied in both protocols. This difference can be modeled as an artificial increase in the burst length in the case of the JIT protocol whereas no increase is introduced to the actual burst length in the case of JET protocol.

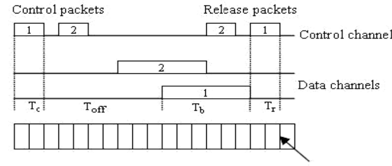

Fig 1 operation in JIT protocol

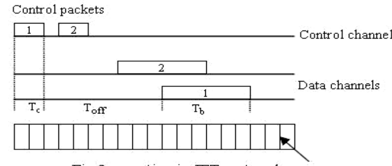

Fig 2 operation in JET protocol

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The aim of this paper is to introduce an enhanced mathematical model which studies the performance of the OBS core node under certain assumptions that will be stated in the next section. Shalaby proposed a simplified model in [2] to study the performance of an OBS core node assuming Bernoulli distribution for arrivals per time slot which proved to be a good assumption till a certain traffic load when compared with the simulation results assuming that arrivals follow Poisson distribution. After this traffic load, the model turned to be non consistent. In addition, it has another limitation where the maximum value for the average number of arrivals per time slot is one. He also assumed a fixed burst length which is not realistic because the burst length depends on the assembly algorithm used by the ingress node to aggregate the packets in a burst [3]. These two drawbacks will be handled in this paper resulting in more consistent results for a wider range of traffic load. In addition, the proposed model deals with the case of no wavelength conversion capability in the OBS node unlike previous models that adopt the M/M/k/k queue to model the performance of the node in which full wavelength conversion is assumed [5]. In our model, assuming the absence of wavelength conversion can be supported by the fact that adding such advanced techniques may raise the overall cost of the node to an unaffordable limit.

The remainder of this paper is organized as follows. In Section II, we present the assumptions on which the mathematical model is built. In Section III, the construction of the state diagram that expresses the performance of the OBS node is provided. Section IV is devoted for a theoretical study for the performance of an OBS network, where derivation of the steady-state system throughput is given. Section V is maintained for the numerical results of the derived performance measure from both the proposed mathematical model and simulation. Finally, we give our conclusion in Section VI.

II. PRE-ANALYSIS MODEL CONSIDERATIONS

The huge number of states required to express a network makes the trace of these states and deriving mathematical expressions governing the performance of this network a very difficult job. Consequently, the proposed model is derived under certain assumptions that are introduced as follows:

1. The system is assumed to be slotted in time such that the time slot "T_s" is the smallest time unit. This will facilitate the construction of the state diagram provided that the time slot chosen is small enough to consider the system continuous in time. Fixed burst length (virtual) is also assumed where $T = l * T_s$ and l is an integer value. This assumption proves to be accepted which will be justified later in the simulation results.
2. In this paper, equilibrium point analysis (EPA) is used such that number of users entering a certain state equal to the number of users departing it i.e. number of served users in each state is always constant [2].
3. We assume without loss of generality that all arrivals require the same output port which can be justified by assuming that the outgoing traffic will be uniformly distributed on all output ports.
4. Since the time slot is very small (to consider the system is continuous in time), we can properly assume that the maximum number of arrivals per time slot is two. Thus, we can approximate the Poisson distribution to be:

$$P_a(n) = \begin{cases} e^{-R_b T_s} \cong 1 - A + \dfrac{A^2}{2} = P_0 & \text{if } n = 0 \\ R_b T_s e^{-R_b T_s} \cong A - A^2 = P_1 & \text{if } n = 1 \\ \dfrac{(R_b T_s)^2}{2!} e^{-R_b T_s} \cong \dfrac{A^2}{2} = P_2 & \text{if } n = 2 \\ \dfrac{(R_b T_s)^n}{n!} e^{-R_b T_s} \cong 0 & \text{otherwise} \end{cases}$$

   where $A = R_b T_s$ denotes average traffic arrivals in Poisson distribution, 'a' stands for arrivals, $n \in \{0,1,2,\ldots\}$ and $P_a(n)$ is the probability of occurrence of n arrivals in a time slot.
5. Unlike all previous work done in the performance modeling of the OBS core network, e.g., in [2], [3] and [5], which assumes full wavelength conversion capability, our model assumes that the OBS core node studied has no wavelength conversion capability which is a reasonable assumption to make. This assumption can be justified by the large expenses needed to implement this technology in the node which might be yet unaffordable.

Another consideration should be taken prior to starting our analysis. Obviously, there are two sorts of scenarios in which blocking may occur at the core node; one of which is due to the collision of two control packets sent on the same control channel, the other is the blocking of a data burst itself when its corresponding control packet fails to reserve a wavelength for it. In either case, the data burst is assumed to be dropped and should be excluded when calculating the throughput.

The first blocking scenario, i.e. the control packet collision, can be resolved by adjusting the appropriate ratio between the control channel group (group of wavelengths dedicated to carry control packets only) and the data channel group (group of wavelengths used to serve data bursts) as proposed in [4]. As a result, the only possible blocking scenario is when the control packet fails to reserve a wavelength for its ensuing data burst.

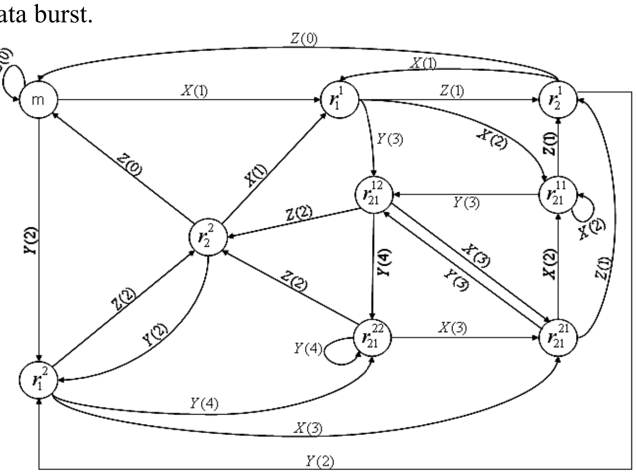

Fig. 3. State Diagram for an OBS network with $l = 2$ and $w \geq 2l$

III. STATE DIAGRAM CONSTRUCTION

In this section, our focus is directed at presenting a detailed state diagram for our OBS network model. As already stated in the assumptions in the previous section, we use the equilibrium point analysis technique (EPA) in constructing the state diagram. It is also assumed that the OBS node considered has no wavelength conversion or buffering capabilities due to lack of resources to cover their costs. From this point on, the OBS node considered is assumed to have w wavelengths available to provide services for the incoming bursts.

Before starting to explain how to construct the state diagram, it should be noticed that any state will be labeled with its probability i.e. the probability for the OBS node to be in this state. The notation used to label each state is based on a general criterion that defines the notation $r_{i_n, i_{n-1},\ldots, i_1}^{j_n, j_{n-1},\ldots, j_1}$ (where $n \in \{1,2,\ldots, l \wedge w\}$, $i_n, i_{n-1},\ldots, i_1 \in \{1,2,\ldots, l\}$ and $j_n, j_{n-1},\ldots, j_1 \in \{1,2\}$ with $l \wedge w = \min\{l, w\}$). It means that the OBS node is currently serving slot i_n of the first j_n arrivals (one or two arrivals), slot i_{n-1} of the next j_{n-1} arrivals (one or two arrivals), and so on. For example, the node is in state r_{31}^{12} when it is serving slot 3 of the first single arrival and slot 1 of the next two arrivals. In addition, the state that represents the case when the OBS node is idle is denoted by m in the state diagram. It models the case when the node is not serving any bursts at all. The transition probability, which is the probability for an OBS node to go from a state to another, is placed at the arrow connecting between the two states.

To simplify the problem of how to construct the state diagram, we start our discussion with a special case of an OBS network with $l = 2$ and $w \geq 2l$. After that, the general case is considered showing how the state diagram can be constructed for an OBS network with any w and l.

A. State Diagram for an OBS Network With $l = 2$ and $w \geq 2l$

In this section, a simple case is chosen as an example to start our discussion with, because it is very tractable especially having a reasonable number of states. The state diagram in this case can be constructed as shown in Fig.3. There are nine states in the state diagram. The transition probabilities are written in terms of X, Y and Z which are defined as functions of k in the following equations:

$$X(k) = P_1 - (k-1)\frac{P_1}{w} + \left(P_2 - (k-1)^2\frac{P_2}{w^2} - \frac{P_2}{w^2}\times {}^{(w-(k-1))}P_2\right)^{\#} \quad (1)$$

$$Y(k) = \frac{P_2}{w^2}\times {}^{(w-(k-2))}P_2 \quad (2)$$

$$Z(k) = P_0 + \left(k\frac{P_1}{w}\right)^{\#} + \left(k^2\frac{P_2}{w^2}\right)^{\#\#} \quad (3)$$

where k is the number of wavelengths used by the OBS node for transmission of bursts at the next state it will enter and ${}^nP_i = \binom{n}{i}\times i!$ is n permutation i. The hash signs added above brackets indicate that terms inside them represent blocking cases. A single hash sign means that a single arrival is blocked (not served), whereas double hash signs mean that two arrivals are blocked.

From the state diagram shown in Fig.3, it is quite simple to write the flow equations from which one can calculate the state probabilities with the aid of the condition that the sum of all state probabilities equals one.

B. State Diagram Construction in the general case (for any w and l)

In this section, we will present a general method that can be applied to construct the state diagram for any w and l.

First of all, we will consider a k-λ state $r_{i_n, i_{n-1},\ldots, i_1}^{j_n, j_{n-1},\ldots, j_1}$ where $i_n, i_{n-1},\ldots, i_1 \in \{1,2,\ldots,l\}$, $j_n, j_{n-1},\ldots, j_1 \in \{1,2\}$, $k \in \{1,2,\ldots, w \wedge 2l\}$, $n \in \{1,2,\ldots, l \wedge w\}$, $k = \sum_{i=1}^{n} j_i$ and $i_n > i_{n-1} > \ldots > i_1$.

Three different scenarios may generate this state. We can categorize all the states found in the state diagram into three main families depending on the scenario that generates it.

1) *Family (1)*: It contains all the states having i_1=1 and j_1=1. That is, the node in these states is serving one new arrival. The previous states that may generate this state are either a (k-1)-λ state $r_{i_n-1, i_{n-1}-1,\ldots, i_2-1}^{j_n, j_{n-1},\ldots, j_2}$ or a k-λ state $r_{l, i_{n-1}, i_{n-1}-1,\ldots, i_2-1}^{1, j_n, j_{n-1},\ldots, j_2}$ or a (k+1)-λ state $r_{l, i_{n-1}, i_{n-1}-1,\ldots, i_2-1}^{2, j_n, j_{n-1},\ldots, j_2}$ (only if $k+1 \leq w$).

The *transition probability* is given by:

P_{tr1} = Pr{one new arrival}×
Pr{the arrival selects an unused wavelength}
+ Pr{two new arrivals}× [Pr{one arrival selects an unused wavelength and the other selects a used one} + Pr{both arrivals select the same unused wavelength}]

The *flow equation* that describes this family is:

$$r_{i_n, i_{n-1},\ldots, i_2, 1}^{j_n, j_{n-1},\ldots, j_2, 1} = X(k)\times\left[\begin{array}{l} r_{i_n-1, i_{n-1}-1,\ldots, i_2-1}^{j_n, j_{n-1},\ldots, j_2} \\ + r_{l, i_{n-1}, i_{n-1}-1,\ldots, i_2-1}^{1, j_n, j_{n-1},\ldots, j_2} \\ + (1-\left\lfloor \frac{k}{w}\right\rfloor)\times r_{l, i_{n-1}, i_{n-1}-1,\ldots, i_2-1}^{2, j_n, j_{n-1},\ldots, j_2} \end{array}\right] \quad (4)$$

where X(k) is slightly different from the definition already stated in equation (1). From this point on, X(k) is defined as follows:

$$X(k) = P_1 - (k-1)\frac{P_1}{w} + P_2 - (k-1)^2\frac{P_2}{w^2} - (1-\left\lfloor \frac{k}{w}\right\rfloor)\times\frac{P_2}{w^2}\times {}^{(w-(k-1))}P_2$$

The term $(1-\lfloor k/w \rfloor)$ is added to make the definition of $X(k)$ hold for the case ($w \leq 2l$) in which some states are no longer present, so the term $(1-\lfloor k/w \rfloor)$ helps cancel the term $\frac{P_2}{w^2}\times {}^{(w-(k-1))}P_2$ in X(k) corresponding to the transition probability of entering the omitted state which are no longer present.

2) *Family (2)*: It contains all the states having i_1=1 and j_1=2. That is, the node in these states is serving two new arrivals. The previous states that may generate this state

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are either a (k-2)-λ state $r^{j_n, j_{n-1}, \dots, j_2}_{i_n-1, i_{n-1}-1, \dots, i_2-1}$ or a (k-1)-λ state $r^{1, j_n, j_{n-1}, \dots, j_2}_{l, i_{n-1}, i_{n-1}-1, \dots, i_2-1}$ or a k-λ state $r^{2, j_n, j_{n-1}, \dots, j_2}_{l, i_{n-1}, i_{n-1}-1, \dots, i_2-1}$.

The *transition probability* is given by:

P_{tr2} = Pr{two new arrivals}×

Pr{both arrivals select unused wavelengths}

The corresponding *flow equation* is thus:

$$r^{j_n, j_{n-1}, \dots, j_2, 2}_{i_n, i_{n-1}, \dots, i_2, 1} = Y(k) \times \begin{bmatrix} r^{1, j_n, j_{n-1}, \dots, j_2}_{l, i_{n-1}, i_{n-1}-1, \dots, i_2-1} \\ + r^{2, j_n, j_{n-1}, \dots, j_2}_{l, i_{n-1}, i_{n-1}-1, \dots, i_2-1} \\ + r^{j_n, j_{n-1}, \dots, j_2}_{i_n-1, i_{n-1}-1, \dots, i_2-1} \end{bmatrix} \quad (5)$$

where Y(k) is already defined by equation (2)

3) *Family (3)*: It contains all the states that are not belonging to family (1) or (2). That is, the node in these states is not serving new arrivals. The previous states that may generate this state are either a k-λ state $r^{j_n, j_{n-1}, \dots, j_1}_{i_n-1, i_{n-1}-1, \dots, i_1-1}$ or a (k+1)-λ state $r^{1, j_n, j_{n-1}, \dots, j_1}_{l, i_{n-1}, i_{n-1}-1, \dots, i_1-1}$ (only if k+1≤w) or a (k+2)-λ state $r^{2, j_n, j_{n-1}, \dots, j_1}_{l, i_{n-1}, i_{n-1}-1, \dots, i_1-1}$ (only if k+2≤w).

The *transition probability* is given by:

P_{tr3} = Pr{no arrivals}+ Pr{one new arrival}×

Pr{the arrival selects a used wavelength}+

Pr{two new arrivals}×

Pr{both arrivals select used wavelengths}

The corresponding *flow equation* is thus:

$$r^{j_n, j_{n-1}, \dots, j_2, j_1}_{i_n, i_{n-1}, \dots, i_2, i_1} = Z(k) \times \begin{bmatrix} (1 - \left\lfloor \frac{k}{w} \right\rfloor) \times r^{1, j_n, j_{n-1}, \dots, j_1}_{l, i_{n-1}, i_{n-1}-1, \dots, i_1-1} \\ + r^{j_n, j_{n-1}, \dots, j_1}_{i_n-1, i_{n-1}-1, \dots, i_1-1} \\ + (1 - \left\lfloor \frac{k}{w-1} \right\rfloor) \times r^{2, j_n, j_{n-1}, \dots, j_1}_{l, i_{n-1}, i_{n-1}-1, \dots, i_1-1} \end{bmatrix} \quad (6)$$

where Z(k) is already defined by equation (3)

IV. Theoretical Analysis and Performance Measures Evaluation

In this section, evaluation of the steady-state system throughput (for any l and w) for the proposed model is provided. A brief explanation for how to derive a closed form for the steady-state system throughput (β) is presented.

First, a MATLAB code is used to solve the exact flow equations describing the state diagram for different values of w and l. A conclusion is reached after observing the state probabilities resulting from the code. This conclusion implies that some state probabilities are approximately equal and this equality holds for different values of w and l. The rule governing this equality is that the OBS node in these states uses the same number of wavelengths (k) and number of single arrivals served by the node at different time slots are equal in the two states i.e. $r^{j_n, j_{n-1}, \dots, j_1}_{i_n, i_{n-1}, \dots, i_1}$ and $r^{j_m, j_{m-1}, \dots, j_1}_{i_m, i_{m-1}, \dots, i_1}$ are said to be equal when $k = \sum_{i=1}^{n} j_i = \sum_{p=1}^{m} j_p$, $n = m$, $j_i = j_p$ where $i \neq p$.

The above approximation will reduce the three families in equations (4), (5) and (6) into two categories described in equations (7) and (8) which are derived after many mathematical manipulations. The states in the two new categories are denoted by $a_{k,n}$ and $b_{k,n}$.

$$a_{k,n} = \sum_{i=1}^{2^{h-1}} \begin{bmatrix} \left[\prod_{j=1}^{h} H\left(k + 1 + \sum_{p=1}^{j} (-1)^{\left\lceil \frac{i}{2^{h-p}} \right\rceil} \right) \right] \\ \times \prod_{q=1}^{h-1} C\left(\left(k + 1 + \sum_{z=1}^{q} (-1)^{\left\lceil \frac{i}{2^{h-z}} \right\rceil} \right) \times \left(1 - \left\lceil \frac{i}{2^{h-1-q}} \right\rceil \bmod 2 \right) \right) \\ \times G\left(k + 1 + \sum_{p=1}^{h} (-1)^{\left\lceil \frac{i}{2^{h-p}} \right\rceil} \right) \\ \times b_{k + \sum_{p=1}^{h} (-1)^{\left\lceil \frac{i}{2^{h-p}} \right\rceil}, \left(k + \sum_{p=1}^{h} (-1)^{\left\lceil \frac{i}{2^{h-p}} \right\rceil} \right) / 2} \end{bmatrix} \quad (7)$$

where

$$H(k) = \frac{X(k)}{1 - X(k-1)}, \; G(k) = \frac{Y(k+1)}{1 - X(k) - Y(k+1)} + 1, \; C(k) = 1 - \left\lfloor \frac{k}{w} \right\rfloor$$

and $h = 2n - k.$

$$b_{k,n} = \left[\prod_{i=1}^{n} [G(k - (2i-1)) - 1] \right] \times m \quad (8)$$

After the calculation of m we can compute the value of any state probability. Consequently, the *steady-state throughput* *β(A,l,w)* can be calculated in equation (9) by simply multiplying each state probability by the number of reserved wavelengths in this state (i.e. the number of successful served bursts in this state).

$$\beta(A, l, w) = \sum_{n=1}^{l \wedge \left\lfloor \frac{w}{2} \right\rfloor} \left[2n \times \binom{l}{n} \times b_{2n,n} \right] + \sum_{n=1}^{l \wedge w} \left[\sum_{k=n}^{w \wedge (2n-1)} \left[k \times \binom{l}{n} \times \binom{n}{2n-k} \times a_{k,n} \right] \right] \quad (9)$$

V. Simulation and Results

As mentioned earlier in section II, the assumption of fixed burst length in the proposed model should be justified. To do so, a simulation work is performed using MATLAB in which a comparison between the steady-state system throughput (β) in two cases is made; first assuming fixed burst length at l = 50 and w = 32, and the second assuming random burst length that follows Gaussian distribution as proposed in [3]. The average value of the Gaussian distribution is set to $\overline{l} = 50$ and w = 32. Results of simulation shown in Fig. 4 reveal that the steady-state system throughput is almost the same in both cases which justifies the assumption of fixed burst length in the proposed mathematical model.

In addition, another simulation work is made to study the OBS network performance, i.e. by calculating the average system throughput (β), assuming exact Poisson traffic arrivals. The results of this simulation will be taken as a reference to compare the results of our proposed mathematical model with, and check its range of consistency

The steady-state system throughput (β), which is assumed to be the performance measure of the OBS core node, is shown in Fig. 5 where it is drawn against the average network traffic arrivals (A) in three different cases. First, the results assuming exact Poisson arrivals, which are obtained from simulation, are drawn. Second, the results of our proposed mathematical model, which are derived from equation (9), are also drawn. Finally, the results of the older mathematical model proposed by Shalaby in [2], which assumes Bernoulli traffic arrivals, are added. Also, to clarify that our proposed model, unlike previous models, assumes the absence of wavelength conversion, we draw the average throughput calculated from the Erlang-B formula derived from the M/M/*w*/*w* model [5] in which the number of servers equal the number of wavelengths and there are no places in the queue. In the Erlang-B formula, full server accessibility is assumed and thus it represents the case of full wavelength conversion capability in the node unlike our model.

Comparing the four curves, one can notice that the system throughput (β) derived using our proposed mathematical model is approximately equal to that obtained from simulation (assuming Poisson arrivals), and this equality holds up to average traffic arrivals of 0.6. On the other hand, it can be noticed that the throughput (β) derived from the older model proposed in [2] is equal to that obtained from simulation only up to average traffic arrivals of 0.12. In the case of M/M/*w*/*w* model, the throughput (β) exceeds that of simulation. This proves that our proposed model provides a much better approximation for the exact case when compared with the older model proposed and more accurate representation of the introduced exact case considering the absence of full wavelength conversion capability compared to M/M/w/w model [5].

The comparison also shows that our model outperforms the older model in terms of the range of consistency. Beyond the limit of consistency, the throughput obtained from our proposed model has larger values compared to the exact case (Poisson arrivals).

The reason behind this model collapse could be returned to a failure in the assumed arrival distribution in our model which limits the maximum number of arrivals in a given time slot to two and thus fails to approximate the Poisson arrivals beyond the limit of consistency.

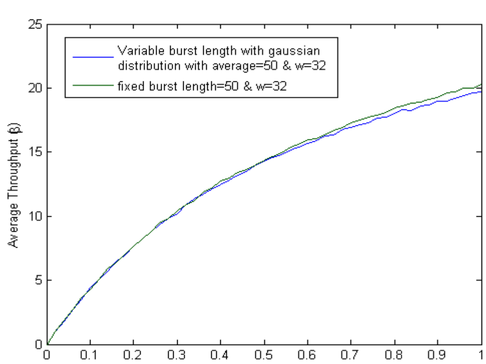

Fig. 4. Average throughput versus average network traffic for fixed burst length and random Gaussian burst length

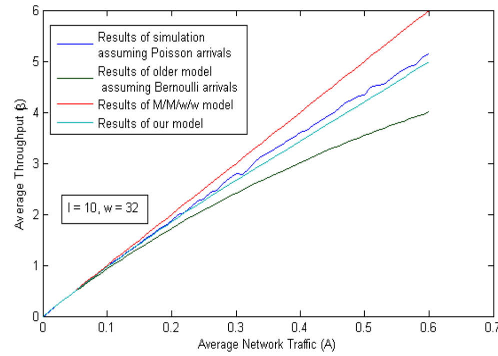

Fig. 5. Average throughput versus average network traffic for the proposed model, for the simulation and for the older proposed model

VI. Conclusion

The enhanced mathematical model evaluates a performance measure of an OBS core node; namely the steady state system throughput, under the assumption of no wavelength conversion in the OBS node. Numerical results are presented at different values of network traffic. Based on the presented results one can come up with the following conclusions:

1) In spite of the complexity of the proposed mathematical model equations, the model is still an easy and reliable way to get fast results by direct substitution with known network parameters instead of great efforts spent on simulation.
2) Throughput results show that our proposed model provide a good approximation for the exact case (Poisson arrivals) and outperforms the older model proposed in [2] in terms of range of consistency.
3) Results also reveal that the proposed model deals with the case of no wavelength conversion capability in the node, unlike older proposed models such as the M/M/*w*/*w* model [5]. This can be the real case due to the large costs needed to install such advanced technologies which may increase the overall cost of the core network to an unacceptable limit.

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