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Modeling and Analysis of WDM OPS Employing Tunable Converter Sharing under Self-Similar Variable Length Packet Traffic

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Abstract—Wavelength division multiplexing (WDM) switching has been emerging as the dominant technology in optical networks. In this paper, we study the switching performance of WDM optical packet switch (OPS) equipped with tunable wavelength converter sharing dedicated to each output fiber line under self-similar variable packet length traffic. In this study, we model WDM OPS employing tunable wavelength converters as a $\mathbf{MMPP/M/W/C}$ queueing system. In our model, packets arriving at OPS are assumed to follow Markov modulated Poisson process (MMPP) that emulates self-similar traffic, and service times (packet lengths) are exponentially distributed to cope with variable packet length. We investigate packet blocking probabilities against traffic load for different wavelength conversion capabilities under self-similar traffic. We propose an efficient analytical method and the results are validated with simulations. We present the computational complexity of the proposed analytical method. Our analysis is more significant in dimensioning WDM OPS to guarantee quality of service (QoS).

Keywords: *Wavelength division multiplexing, Optical packet switching, wavelength converter sharing, self-similar traffic, blocking probabilities.*

I. INTRODUCTION

Advances in Optical Communication have led to the demand of efficient switching devices in Optical Networks. Wavelength division multiplexing (WDM) has emerged as a viable solution to the increasing bandwidth demands of current backbone networks. On the other hand, Internet traffic is shown to be long range dependent or self-similar [1]. To cope with this kind of traffic and for more effective utilization of fiber capacity, new packet-based optical switching paradigms have been introduced, known as Optical Packet Switching (OPS) and Optical Burst Switching (OBS) [2-3]. These are still active areas of research. In an OPS network control and data information are sent simultaneously on the same channel. Each intermediate node converts the control header to take the switching decisions while the packets always remain in the optical domain. In the OBS network, the control and data information travel separately on different channels. Control packets are sent first to reserve the resources in intermediate nodes along end to end path. The data burst follows the control packet with some offset time [3]. We consider the blocking model described in [4], in which light paths are set and torn down at the packet level. In general, OPS network are divided into two categories, synchronous (slotted) and asynchronous (unslotted) [2]. In a synchronous OPS network, all the packets have the same size and are assumed to arrive at slot boundaries [2]. In asynchronous networks packets can have variable sizes and are not aligned before they enter the OPS. Implementation of synchronous OPS nodes with high data rates is more costly, since it requires synchronization of all incoming packets in the optical domain [5]. However, performance analysis of synchronous OPS has already been studied in [6]. In asynchronous OPS networks the node architecture is simpler because there is no need for the synchronization of packets. Moreover, as mentioned in [5] IP packets are of variable length therefore for switching IP packets asynchronous operation is quite suitable. To these justifications, it is meaningful to consider asynchronous OPS for IP based network traffic.

In asynchronous optical packet switching packet contention is a major issue. Contention arises when two or more incoming packets are contending for the same output wavelength port. In such a case only one packet can be forwarded to the output port while other packets will be dropped. This will lead to lower utilization of the OPS. The contention can be resolved by any of the following approaches: deflection routing [3], optical buffering (fiber delay lines) and wavelength conversion (WDM). Deflection routing, in this approach, packets in contention are deflected to output ports other than the desired one. As a matter of fact, part of the network is used as buffers to store these packets. Deflection routing may not be effective for a network with high degree of connections, or a network with heavy traffic load. Another disadvantage of deflection routing is that it introduces extra link propagation delays and causes packets to arrive out of order. FDLs are fibers of fixed lengths, and can hold a packet for a fixed amount of time determined by the speed of light and the length of the FDL. Hence, unlike electronic RAM, FDLs cannot store a packet indefinitely. Once a packet has entered into FDL, it cannot be retrieved until it emerges on the other side. However, for asynchronous variable length packets, the FDL buffer cannot guarantee low packet blocking due to its discrete step delay even if void filling scheduling algorithms are adopted. Furthermore, FDLs can be bulky and expensive, and introduce quality degradation to optical signals.

Wavelength conversion [4] is the ability to convert an optical signal on a given input wavelength to some other output wavelength. One of the most important applications of wavelength conversion is as a mechanism for contention resolution that can dramatically improve the utilization of resources in an optical network, especially in highly dynamic traffic environments such as OPS. Wavelength conversion is the most effective method for contention resolution, not incurring any additional latency. Consequently, wavelength converters have become vital to the

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design of optical buffer and switch architectures for OPS networks. . In general there are two types of conversions Full Wavelength Conversion (FWC) and Partial Wavelength Conversion. In FWC, an arriving packet from a certain wavelength channel is converted to any other idle wavelength channel towards its destination. FWC reduces packet blocking probabilities significantly, compared with the case of No Wavelength Conversion (NWC) [11]. However, implementing FWC is very costly. In PWC, there is limited number of converters and consequently some packets cannot be switched towards their destination, when all converters are busy despite the availability of free wavelength channels on the output fiber. PWC is proposed as a cost aware alternative to FWC.

Wavelength conversion in WDM OPS networks is considered here to perform contention resolution by application of converter sharing using Tunable Wavelength Converters (TWCs) [10], for switching packets from any input wavelength onto any desired output wavelength. There are two types of TWCs sharing architecture, shared-per-node (SPN), where a pool of TWC is shared between all input fibers and channels, and shared-per-link (SPL), where each output fiber has a dedicated pool of TWCs. Although, the SPN architecture leads to better performance, the complexity of the switching matrix is lower in SPL architecture [12]. The main focus in this study will be on SPL architecture.

In this paper, we study the packet blocking probabilities under full conversion, partial conversion and no conversion. The Markovian analysis is carried out in [5] and [16] for synchronous switching. Similarly in [10], exact blocking analysis presented for bufferless asynchronous optical packet switch with SPL-type converter sharing using usual Poisson arrival and exponential packet length assumptions. On the other hand, the authors of [17] study asynchronous SPN system and propose a new suite of methods to reduce the complexity of multidimensional Markov chain. All these studies assume full range shared wavelength conversion. Partial wavelength conversion studies are rather rare. In [11], the authors provide an approximate method for SPL type converter sharing using limited range TWCs. In [18], performance analysis of bufferless optical packet switch employing SP TWCs is presented. To the best of our knowledge, all these studies didn't consider the impact of self-similarity, which emulates the real-time traffic, against Tunable Wavelength Converter sharing in asynchronous WDM OPS. We also present an efficient analytical method based on matrix–analytic approach, which can substantially reduce the computational complexity of multiple server queues with Markov modulated Poisson arrival process. In addition, simulations are developed in order to validate the results of proposed analytical method.

The proposed architecture of WDM OPS employing tunable wavelength conversion sharing is an SPL type converter sharing, shown in Fig. 1. There are 'L' input and 'L' output fiber lines, each fiber line has 'C' wavelength channels and a Tunable Wavelength Converter Pool (TWCP) of size W, $(0 \leq W \leq C)$, dedicated to each output fiber. If $W = 0$ and $W = C$, which correspond to no wavelength conversion and FWC architectures, respectively.

When the wavelength conversion is employed, i.e $0 \leq W \leq C$, then WDM OPS can be modeled as a $MMPP/M/W/C$ queueing system, depicted in Fig. 2. The traffic aggregated at the TWCP of one of the output fiber lines is MMPP modeled self-similar traffic. The number of converters, W, in TWCP is equivalent to the number of servers. The number of channels, C, in each fiber line is equal to the capacity of the queueing system. As the packet lengths are variable, service times are considered as exponential [9]. Now it is apparent, the performance study of WDM OPS employing tunable wavelength conversion sharing is the same as analyzing the packet blocking probabilities of $MMPP/M/W/C$ queueing system. Now, in case of full-range wavelength conversion TWCP size, W, is equal to number of channels in fiberline i.e, $W = C$, then WDM OPS system behaves as an $MMPP/M/C/C$ loss system. In case of no conversion, i.e, for $W = 0$, it is the same as C independent single server $MMPP/M/1/1$ queueing system.

Now it is evident that computing packet blocking probabilities is very crucial in evaluating the performance of OPS with a certain contention resolution capability. In this paper, we focus on the performance analysis of WDM OPS, by studying packet blocking probabilities for tunable wavelength conversion sharing capabilities, under self-similar variable length packet traffic.

The rest of the paper is structured as follows. In Section II, we explain self-similar process and the fundamentals of MMPP processes. In Section III, queueing model and pertinent analysis is presented. Computational complexities of proposed analytical method are discussed in Section IV. Numerical results are presented in Section V. A conclusion is provided in the final section.

II. SELF-SIMILAR TRAFFIC AND MMPP ARRIVAL PROCESS

A. Self-Similar Traffic

Internet traffic is more bursty and this can be characterized mathematically as a Long Range Dependent (LRD) or self-similar traffic [1]. Self-similarity describes the phenomenon when a certain property of an object is preserved with respect to scaling in space or time. The definition of the exact second order self-similar processes is given as follows. Consider the arrival instance modeled as point processes. Let X be a second order stationary process with the variance, σ^2, and divides the time axis into disjoint intervals of unit length. Let $X = \{ X_t : t = 1,2, \dots \}$ be the number of points in the t^{th} interval. For each $m = 1,2,3, \dots$ we consider a new sequence $X_t^{(m)}$ which is obtained by averaging the original sequence in non-over lapping blocks. That is,

$$X_t^{(m)} = \frac{1}{m} \sum_{i=1}^{m} X_{(t-1)m+i}, \quad t = 1,2,3, \dots \qquad \dots (1)$$

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The new sequence is also a second order stationary process and the definition of the exact second order self-similar process based on the variance is given below.

Definition 1: The process 'X' is called exactly second order self-similar with Hurst parameter, $H = 1 - \beta/2$, if

$$Var\left(X^{(m)}\right) = \sigma^2 m^{-\beta}, \quad \forall m > 1 \qquad \dots (2)$$

Self-similar traffic exhibits the properties of burstiness in many or all time-scale range, which is quite different from traditional short range dependent traffic models. However, one may emulate the self-similarity over the desired time-scale range by using MMPPs to fit the exact second order self-similar processes [7, 8].

B. MMPP Arrival Process

MMPP is the doubly stochastic Poisson process whose arrival rate is given by $\lambda^*[J(t)]$, where $J(t), t \geq 0$, is an m-state irreducible Markov process. Equivalently, Markov-modulated Poisson process can be constructed by varying the arrival rate of Poisson process according to an m-state irreducible continuous time Markov chain which is independent of the arrival process. When the Markov chain is in state i, arrivals occur according to Poisson process with rate λ_i. The MMPP is parameterized by the m-state continuous-time Markov chain with infinitesimal generator Q and m Poisson arrival rates $\lambda_1, \lambda_2, \dots, \lambda_m$. We use the notation

$$Q = \begin{bmatrix} -\sigma_1 & \sigma_{12} & \cdots & \sigma_{1m} \\ \sigma_{21} & -\sigma_2 & \cdots & \sigma_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1} & \sigma_{m2} & \cdots & -\sigma_m \end{bmatrix} \qquad \dots (3)$$

$$\sigma_i = \sum_{\substack{j=1 \\ j\neq i}}^{m} \sigma_{ij},$$

$$\Lambda = diag(\lambda_1, \lambda_2, \dots, \lambda_m), \qquad \dots (4)$$

In the following, this MMPP is assumed to be homogeneous, i.e., Q and Λ do not depend on the time t. The steady state probability distribution vector of the Markov chain is π such that

$$\pi Q = 0, \quad \pi e = 1 \qquad \dots (5)$$

where, $e = (1,1,\cdots,1)^T$ is the column vector of length m.In the 2-state case, Q , Λ $and \pi$ are given as follows:

$$Q = \begin{bmatrix} -c_1 & c_1 \\ c_2 & -c_2 \end{bmatrix}, \ \Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \qquad \dots (6)$$

$$\pi = (\pi_1, \pi_2) = \frac{1}{c_1 + c_2}(c_2, c_1) \qquad \dots (7)$$

The interesting feature of MMPP is that a superposition of MMPPs is again MMPP. Special cases of the MMPP are the switched Poisson process (SPP), which is a two-state MMPP, and the interrupted Poisson process (IPP), which is an SPP with one of the arrival rates being zero, in our analytic and simulation models we take $\lambda_2 = 0$, in equation (6).

III. QUEUEING MODEL AND PERTINENT ANALYIS

Markovian analysis for the tunable wavelength conversion is as follows. Let the service time is generally and identically distributed with distribution function $H(t)$. Let $A_n(t), n \geq 0$, denote an $m \times m$ matrix whose $(i,j)^{th}$ element represents the conditional probability that n packets arrive at the system during service time and the underlying Markov chain is in phase j at the end of service given that the underlying Markov chain is in phase i at the beginning of the service. Then, $A_n(t)$ satisfies the following equation:

$$\sum_{n=0}^{\infty} A_n(t) Z^n = \int_0^t e^{[Q-\Lambda+\Lambda z]\tau} \, dH(\tau) \qquad \dots (8)$$

When the service time is exponential with service rate μ , then the eqn. (8) becomes [13]

$$\sum_{n=0}^{\infty} A_n Z^n = \mu^2 \sum_{n=0}^{\infty} \left[\frac{Q-\Lambda+\Lambda Z}{\mu}\right]^n \qquad \dots (9)$$

where, the matrices $A_n' s$ can be computed using the recurrence formula [13].

Next, we consider the embedded Markov chain $\{L(n), J(n)\}, n \geq 0$, at the departures of the queueing system on the state space $\{0,1,2, \dots C\} \times \{1,2, \dots m\}$, where $L(n)$ and $J(n)$ denote the TWCP occupancy and the state of MAP, respectively. At the steady state, the transition probability matrix corresponding to the departure points, P (with the dimension $(C+1)m \times (C+1)m$), is as follows:

$$P = \begin{bmatrix} A_0 & A_1 & \dots & A_W & A_{W+1} & \dots & A_{C-1} & B_C \\ A_0 & A_1 & \dots & A_W & A_{W+1} & \dots & A_{C-1} & B_C \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ A_0 & A_1 & \dots & A_W & A_{W+1} & \dots & A_{C-1} & B_C \\ A_0 & A_1 & \dots & A_W & A_{W+1} & \dots & A_{C-1} & B_C \\ 0 & A_0 & \dots & A_{W-1} & A_W & \dots & A_{C-2} & B_{C-1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & A_0 & A_1 & \dots & A_{W-1} & B_W \end{bmatrix} \dots (10)$$

In (10), elements of the first $W+1$ rows are identical and $B_n = \sum_{i=n}^{\infty} A_i$ denote the probability that there are at least n arrivals. Next let x_k, $0 \leq k \leq C$, denote $1 \times m$ vector whose i^{th} element represents the steady state joint probability that the number of packets in the system at departures is k and the phase of the arrival process is i . In the steady state, we can find the

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vector $x = \{x_k\}$ according to the steady state equation $xP = x, xe = 1$. Although, the general relationship between the probability generating function of queue length at arbitrary time points and that of departure points hold good [14] in case of multiple server queues with finite buffer. Multi-server phenomenon makes it hard to establish an explicit formula for packet blocking probability unlike the single server case in [15]. Instead, we compute the packet blocking probability vector at departure epochs owing to fact that packet block is due to un-availability of TWC.

Let PB be the number of packets blocked due to the fact that wavelength converter is not available in TWCP. Then the expected value of PB can be evaluated as

$$E[PB\} = \sum_{i=0}^{C} \sum_{j=1}^{\infty} j\, x_i A_{C+W(i+j)}\, e \qquad \ldots (11)$$

by considering the last column of the $(C+1) \times (C+1)$ block transition probability matrix P. Then the packet blocking probability PBP can be obtained by

$$PBP = \frac{E[PB]}{\rho} \qquad \ldots (12)$$

where ρ is traffic intensity. The above analysis is applies to the case where $0 < W < C$ the special case of $W = 0$ and $W = C$ are analyzed next.

(i) Full Wavelength Conversion

In case of full-range wavelength conversion TWCP size, W is equal to the number of channels C, then WDM OPS can be modeled as $MMPP/M/C/C$ loss system. In this case, the transition probability matrix P,

$$P = \begin{bmatrix} A_0 & A_1 & A_2 & \cdots & A_{C-1} & B_C \\ A_0 & A_1 & A_2 & \cdots & A_{C-1} & B_C \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_0 & A_1 & A_2 & \cdots & A_{C-1} & B_C \\ A_0 & A_1 & A_2 & \cdots & A_{C-1} & B_C \end{bmatrix} \qquad \ldots (13)$$

on similar approach, packet blocking probability can be computed by using the equations (12) and (13) with $W = C$.

(ii) No Wavelength Conversion

In the case of no conversion, i.e, for $W = 0$, the switch can be modeled as $MMPP/M/1/1$ queueing system and in this case the transition probability matrix P is given by

$$P = \begin{bmatrix} EA_0 & EB_1 \\ A_0 & B_1 \end{bmatrix} \qquad \ldots (14)$$

In eq. (14), $E = (Q-R)^{-1}R$ and consists of conditional probabilities that server is ideal. The packet blocking probability can be computed following the case of single server finite buffer queueing system as in [9].

IV. COMPUTATIONAL COMPLEXITY OF STEADY STATE PROBABILITY VECTOR

It is worthwhile to investigate the required computation complexity of computation of steady state probability vector. Analysis of computation complexity of $MMPP/M/W/C$ queueing system will be useful in deciding the necessary platform for analyzing WDM OPS employing wavelength conversion under variable length self-similar traffic. First we shall present method to compute the steady state vector, and then we derive the computation complexity of the same as follows. The matrix P of eq.(10) is not of the canonical $M/G/1$ type. However, it is possible to take advantage of Schur-Banachiewicz inversion formula for P [19]. Accordingly, the steady state probability vector x is given by $= [0,0,\ldots,0,1](\mathrm{I}-\mathrm{P}_1)^{-1}$, where I is the unit matrix of appropriate dimension and P_1 is the matrix P in which the last column is replaced by $[-1,-1,\ldots,-1,0]^{\mathrm{T}}$. Let $[\mathrm{E_C}, \mathrm{E_C}, \ldots, \mathrm{E_C}, \mathrm{E_{C-1}} \ldots \mathrm{E_W}]^{\mathrm{T}}$ be the last column of P_1. Multiplying the permutation matrix S by $(\mathrm{I}-\mathrm{P}_1)$, we have :

$$S(I-P_1) = \begin{bmatrix} -A_0 & -A_1 & \ldots & -A_W & -A_{W+1} & \ldots & -A_{C-1} & -E_C \\ 0 & -A_0 & \ldots & -A_{W-1} & -A_W & \ldots & -A_{C-2} & -E_{C-1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & -A_0 & -A_1 & \ldots & -A_{C-W-1} & -E_{C-W} \\ I-A_0 & -A_1 & \ldots & -A_W & -A_{W+1} & \ldots & -A_{C-1} & -E_C \\ -A_0 & I-A_1 & \ldots & -A_W & -A_{W+1} & \ldots & -A_{C-1} & -E_C \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ -A_0 & -A_0 & \ldots & I-A_W & -A_{W+1} & \ldots & -A_{C-1} & -E_C \end{bmatrix} \qquad \ldots (13)$$

where

$$S = \begin{bmatrix} 0 & 0 & \cdots & 0 & I & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & I \\ I & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I & 0 & 0 & \cdots & 0 \end{bmatrix} \qquad \ldots (14)$$

The matrix $S(I-P_1)$ can be represented by the following form:

$$S(I-P_1) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \qquad \ldots (15)$$

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Dimensions of A, B, C, and D are $(W+1)\times(W+1)m$, $(W+1m\times C-Wm$, $C-Wm\times W+1m$ and $C-Wm\times C-Wm$, respectively. Using the Schur-Banachiewicz formula for the inverse of block matrices, we could obtain

$$[S(I-P_1)]^{-1} = \begin{bmatrix} A^{-1}+E\Delta^{-1}F & -E\Delta^{-1} \\ -\Delta^{-1}F & \Delta^{-1} \end{bmatrix} \quad \ldots (16)$$

where $\Delta = D - CA^{-1}B$, Schur complement of A, $E = A^{-1}B$, and $F = CA^{-1}$. Since $(I-P_1)^{-1} = [S(I-P_1)]^{-1}S$, steady state probability vector is the last row of the matrix$(\Delta^{-1} - \Delta^{-1}F)$. The Matrix Δ is non-singular, if A is non-singular. The matrix A is upper-triangular Toeplitz matrix whose inverse is easy to compute. The computation complexity to compute its inverse is of order $O(W^2m^3)$. The computational complexity to compute $F$is of order $O((C-W)W^2m^3$. The computational complexity of FB and $\Delta^{-1}F$is of order $O((C-W)W^2m^3$. Therefore, overall complexity to compute the steady state vector is of order $(\max[(C-W)W^2m^3, (C-W)W^2m^3])$.

V. NUMERICAL RESULTS

In this section, we examine the performance of proposed model. Analytical model is evaluated in MATLAB and all the simulations are developed in C++. Each simulation result for the blocking probability is obtained by means of five independent runs where an over all 10^8optical packets are simulated at each run. We compare the results between the analytical and simulations for all the cases presented in this paper. It can be seen that the results match closely indicating that the analytical models are quite accurate in estimating the blocking probabilities for TWCs. Self-similar traffic under taken in this study is fitted by superposition of four 2-state IPPs and a Poisson process following the generalized variance based method [6]. For the numerical results, for full conversion we take TWCP size $W=4$, for partial conversion $\mathrm{W}=2$ or 3 and $W=1$ for no conversion. Packet blocking probabilities are evaluated against the traffic load on the output fiber lines, for different values of Hurst parameter (degree of self-similarity), $H=0.7$, 0.8 and 0.9, variance$(\sigma^2)=0.6$ and mean arrival rate $(\lambda)=1$. MMPP is fitted for these values over the time scale $[10^2, 10^7]$ as in [9]. Figs 3, 4 and 5 illustrate the comparison of packet blocking probabilities of analytical and simulations, against the load of fiber lines for conversion and without conversion. The general observations from these results are: As expected, packet blocking probabilities increase as load increases and decrease as number of wavelength conversions increase. The noteworthy observation is the advantage of adopting wavelength conversion is obvious when the load is moderate, i.e., employing more number of tunable wavelengths lead to better performance. When the load is high the advantage of employing wavelength conversion is limited. This phenomenon is almost in agreement with the conclusions presented in [5]. Fig. 6 indicates the results corresponding to the impact of self-similarity on wavelength conversions. From these results, we observe that packet blocking probabilities are high as H increases. Fig. 7 shows the comparison of packet blocking probability against the number of tunable wavelength converters when the load is 0.85 and for three different values of H=0.7, 08 and 0.9. From Fig. 7, we observe that benefit of wavelength conversion is remarkable when the intensity of self-similarity is reasonable. However, this benefit reduces significantly when self-similarity (H) is high.

IV. CONCLUSIONS

In this paper we have investigated the performance of WDM OPS employing tunable converter sharing under self-similar variable length traffic. We leverage the results of MMPP to emulate self-similar traffic to study the impact of wavelength conversion capabilities of WDM OPS. We have presented an efficient analytical method and the results are closed to the simulation results. We have also proposed an efficient procedure to reduce large computation efforts in solving $\mathrm{MMPP/M/W/C}$ queues and also discussed the computational complexity in brief. The immediate implication of this study is that, performance of the switch not depends only on the number of converters, but there is also a significant impact of self-similar traffic. These findings are very constructive in dimensioning WDM OPS for the next generation optical networks.

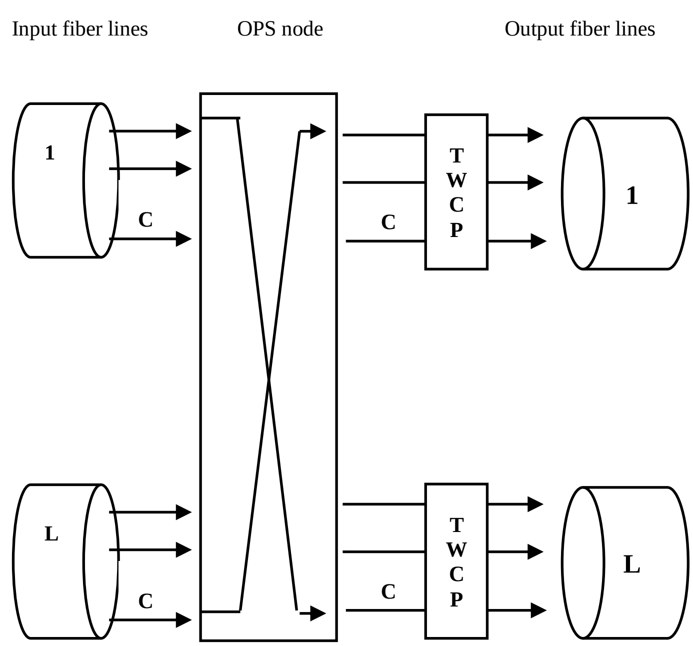

Figure 1. Architecture of SPL type of OPS node, '*L'* I/O fiberlines, each with '*C'* no. of channels and Tunable Wavelength Converter Pool (TWCP) of size '*W*'

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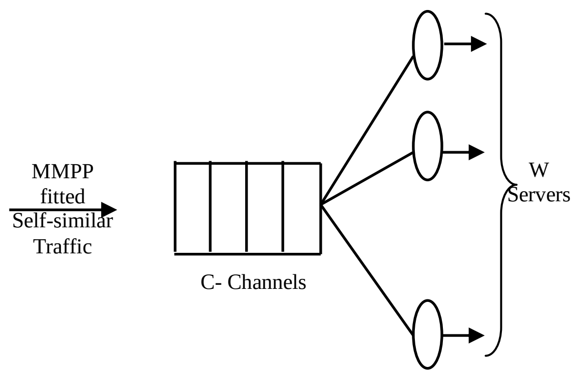

Figure 2. *MMPP/M/W/C* - The equivalent queueing model of WDM OPS depicted in Fig. 1

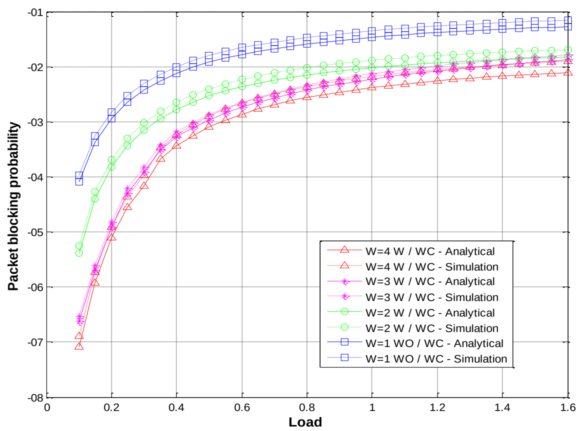

Figure 3. Packet blocking probabilities of *MMPP/M/W/C*, when *H=0.9, C=4, W* – number of wavelength converters, *WO /WC* - without wavelength conversion, *W/WC* – with wavelength conversion.

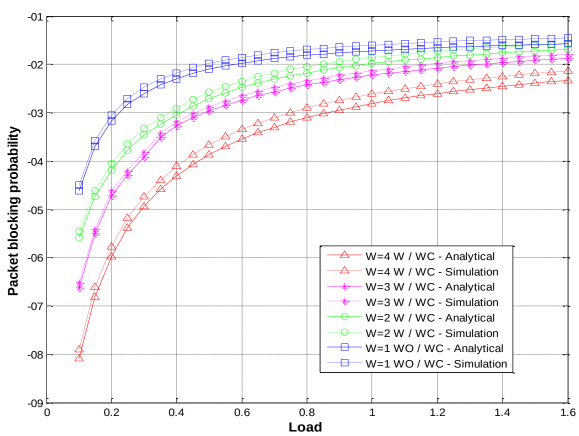

Figure 4. Packet blocking probabilities of MMPP/M/W/C, when H=0.8, C=4, W – number of wavelength converters,WO /WC - without wavelength conversion, W/WC – with wavelength conversion

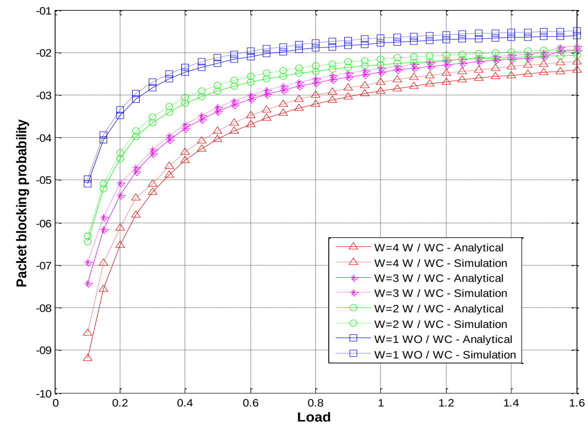

Figure 5. Packet blocking probabilities of MMPP/M/W/C, when H=0.7, C=4, W – number of wavelength converters, WO /WC - without wavelength conversion, W/WC – with wavelength conversion.

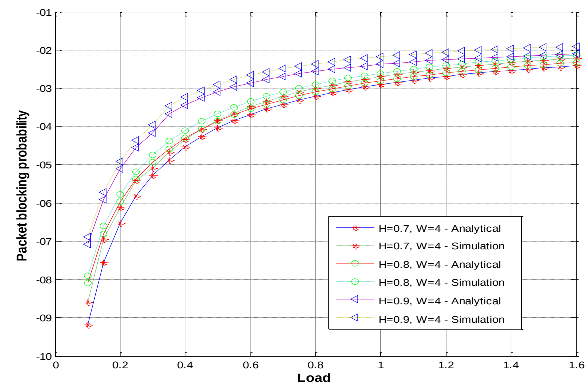

Figure 6. Comparision of packet blocking probabilities of MMPP/M/W/C when H=0.7, 0.8 and 0.9, C=4, W = 4, W – number of wavelength converters.

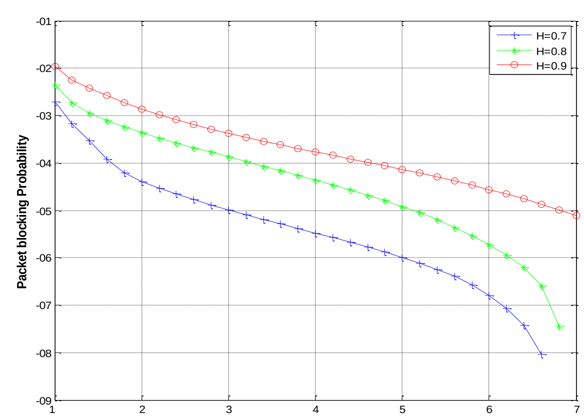

Figure 7. Comparision of packet blocking probabilities of MMPP/M/W/C aginst No. of tunable wavelengtht converters, when H=0.7, 0.8 and 0.9 and the Load is 0.85.

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