A Surjective-Mapping Based Model for Optical Shared-Buffer Cross-Connect

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***Abstract*—A Surjective-Mapping based Model (SMM) is developed to evaluate the performance of a slotted optical shared-buffer cross-connect. The model is simple, accurate, and yet provides comprehensive performance characteristics of the switch. The model also overcomes the limitations of traditional Markovian based models in evaluating moderate to large switches, associated with the explosion of number of states. The model is verified using simulation results for different switch sizes and different numbers of delay lines. The model enables dimensioning the switch architecture to meet the target performance. Performance of optical shared-buffer cross-connect is analyzed in detail, in terms of blocking probability, delay distribution, and delay line utilization.**

***Index Terms*—Combinatorics, optical communication, packet switching, shared memory, simulations.**

I. INTRODUCTION

OPTICAL packet switching and burst switching are two main strategies to achieve high-speed data transmission networks that are transparent and reconfigurable. In such switches, when two or more packets or bursts are addressed to the same output port simultaneously, only one is assigned that port, and the remaining contenders may be dropped. One of the main challenges in achieving effective contention resolution in optical switches is the lack of an optical random-access memory (RAM) similar to that utilized in the electronic switches. The contention resolution schemes in optical switches include exploiting wavelength dimension [6], space dimension [5], and time dimension [13].

In wavelength based contention resolution schemes [6], a wavelength converter is utilized such that one of the contending packets is assigned the desired wavelength, while the rest are converted to unused wavelengths in the same output port. Space based contention resolution schemes [5] include employing multiple output fibers and utilizing deflection routing. The approach of employing multiple output fibers [10], [18], is conceptually similar to that of the wavelength conversion; however, in this case, multiple output fibers connecting the nodes are utilized instead of multiple wavelengths. With deflection routing [8], [21], one of the contending packets is assigned the preferred output port while others are deflected to the non-preferable output ports. The drawback of this approach is that the deflected packet may have to traverse a longer path to reach the destination, which may also result in a significant crosstalk noise in the optical signal. Furthermore, the network becomes more congested as more deflections take place [19].

Time based contention resolution schemes may be implemented by utilizing fixed-length Fiber Delay Lines (FDLs). In these schemes, optical packets propagate through each FDL on a *first-in-first-out* basis for a fixed amount of time. The propagation time delay is usually chosen to be a multiple of the packet transmission time. Optical buffering schemes that use FDL for contention resolution can be divided into two categories: feed-forward [9], [11], [14], [15], and feedback FDL buffering [1], [3], [12], [17]. In feed-forward buffering, a contending packet is delayed at the output port and leaves the node after the propagation delay of the traversed FDL. In feedback buffering, also called optical shared-buffering, the delayed packet re-enters the node after the propagation delay of the FDL. A transform based analysis is conducted in [15] to derive an approximation for the loss probability of switches with feed-forward FDLs.

With feedback architecture, all FDLs are shared by all packet arrivals including those arriving from the FDLs to the switch. Therefore, a shared-FDL cannot be analyzed as an isolated module due to the interdependency among arrivals from different input ports to the switch [1]. Nevertheless, feedback architecture achieves better performance in terms of the packet loss rate than that achievable through a comparable feed-forward architecture [16].

Although models are available for modeling optical shared-buffer switch, in this paper, we develop an accurate yet simpler model that provides a comprehensive insight into its performance characteristics. A simulation based performance analysis of a slotted optical packet switch with a feedback buffer configuration as well as wavelength conversion is presented in [3]. Slotted optical switches require synchronization, which is complicated to implement in the optical domain. Furthermore, the packet size needs to be deterministic. However, slotted operation makes the control of the switch significantly less complex. The study of unslotted optical shared-buffer switches in [12] considers variable length packets. Both feedback and feed-forward FDL based optical switches are studied in [16]. A Markovian based model for a asynchronous optical burst switch architecture employing feedback optical buffering is presented in [17], where bounded delay characteristics of FDLs are captured. A shared-buffer switching architecture similar to that presented in Fig. 1 is analyzed based on a Reduced Markov Chain (RMC) in [1]. This RMC model significantly reduces the number of states compared to that of Full Markov Chain (FMC)

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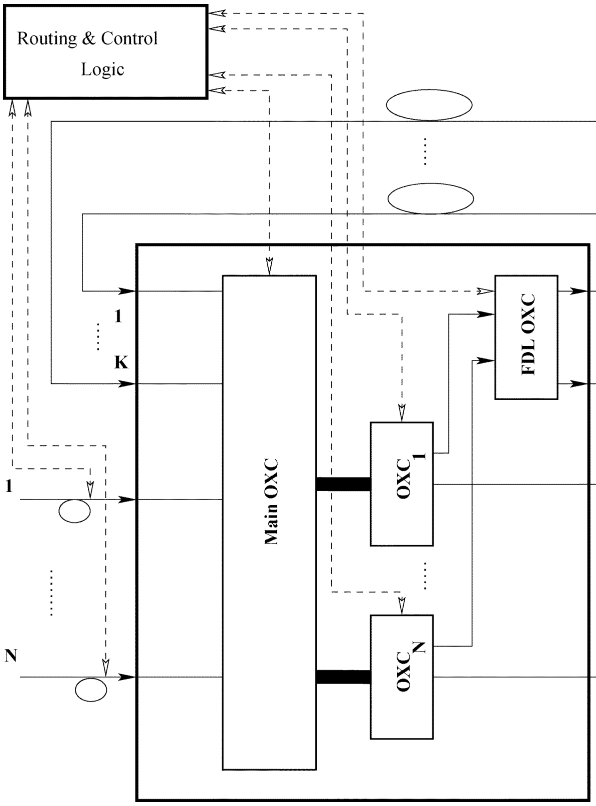

Fig. 1. Optical packet switch with feedback FDLs.

based model previously developed to study similar architectures [20]. While RMC model provides results similar in accuracy to that of FMC models, in terms of packet loss probability, it is still limited to a switch with a small nodal degree and small number of FDLs. A switch with a nodal degree of $N = 16$ and $K = 8$ FDLs is represented by a 922-state RMC. The authors provide a simplified construction methodology that makes the RMC tractable for a switch of small size. However, the number of states for modeling a switch explodes and becomes untractable for higher values of N and K.

Thus far, papers on performance evaluation of the optical shared-buffer switch present a limited characterization of the performance metrics of the switch compared to what is presented in this paper. We follow a new approach, based on the Surjective-Mapping based Model (SMM), to model the shared-feedback FDL optical switch. The model is simple, tractable, and yet provides a comprehensive insight into the performance of the optical shared-buffer switches. The model is also applicable for evaluating large switches. For instance, a set of 922 equations are generated using RMC approach for a switch with $N = 16$ and $K = 8$, while a set of only $(N + K)$ equations are generated using SMM approach to study the same switch. Therefore, the model provides a method to evaluate performance of switches significantly larger than what RMC based models can feasibly capture. Moreover, SMM model provides full characteristics of the traffic flow at different stages inside the switch. Simulation based results are used below to verify the analytical results generated using SMM based model.

Section II presents the basic architecture of the optical shared-buffer switch. Section III derives the SMM model, and presents formulas for evaluation of different performance parameters. Section IV presents performance results, based on both analytical and simulation models, of optical shared-buffer switches with different configurations. Finally, Section V provides the conclusions.

II. OPTICAL SWITCH WITH FEEDBACK SHARED-BUFFER

Fig. 1 shows the optical shared-buffer switching architecture that is evaluated in this paper. The $N \times N$ switch consists of N primary inputs and N primary outputs. The switch is augmented with K FDLs. Each fiber line can either be passive or augmented with an amplifier [1]. The inputs to the switch from the K FDLs will be referred to as secondary inputs. The propagation delay of each line is equal to the time period of a single slot. A slotted system is considered where the duration of the slot is equal to the transmission time of packets of fixed length. After propagating in a delay line, a packet presents itself back at the inputs of the switch and competes for the required output port in the following time slot. The main optical cross-connect (*Main OXC*) switches packets arriving on primary and secondary inputs to the output *OXC* corresponding to the destination address of the packet. If only one packet is forwarded to an *OXC*$_i$, it is forwarded to the output port i. When multiple packets compete for the same port, the related *OXC* forwards one of the packets, chosen randomly, to that output port while forwarding the rest of the competing packets to the FDLs' cross-connect, *FDL OXC*, which forwards the packets to the FDLs. If the number of incoming packets to *FDL OXC* is greater than K, the total number of FDLs, K packets, randomly chosen, are forwarded to the K available FDLs and the rest of the packets are dropped. Note that the criteria for selecting a packet to be dropped can be selecting the packet that has encountered the longest delay among the competing packets. Some other criteria for selecting a packet to be dropped can also be considered. The packets to be dropped are selected randomly in deriving the model; however, the values for throughput, loss probability, and delay line utilization are still valid regardless of this scheme.

III. PERFORMANCE ANALYSIS

This section presents the SMM based performance model. The model addresses the symmetric case where the load is uniformly distributed among the primary input ports, and destinations of packets are (*iid*) uniformly distributed among the primary output ports. The switch operates in a slotted mode, in which incoming packets are aligned at the inputs, and all are processed and switched during a time slot. Let X and Y be the random variables representing the number of packets present in a given time slot at the secondary and primary inputs, respectively. X takes values from 0 to K while Y takes values from 0 to N. Note that, at each time slot, the number of packets arriving at the secondary inputs (X) is assumed to be independent and identically distributed (*iid*) random variables, each of which is thus represented by X. The probability that a packet arrives at one of the primary input lines in a given time slot is denoted by ρ, which corresponds to the normalized offered load. Finally, the destinations of packets arriving at the secondary inputs in a given time slot are assumed to be independent of packets arriving at both primary and secondary inputs in the previous time slots. Since packet arrivals at primary inputs are assumed to be independent of each other, the number of packet arrivals at the primary inputs in a given time slot follows the binomial distribution, i.e.,

$$P(Y=y)=\binom{N}{y}\rho^{y}\left(1-\rho\right)^{N-y}. \tag{1}$$

Let Z be the random variable representing the total number of packets arriving at both primary and secondary inputs, i.e.,

$$Z=X+Y. \tag{2}$$

The packet arrivals during a given time slot at the primary inputs, represented by Y, are assumed to be independent of the packet arrivals during the previous time slot, on which the random variable X depends. Therefore, the distribution of Z is given by

$$P(Z=z)=\sum_{x=0}^{z}P(X=x)P(Y=z-x). \tag{3}$$

Note that Z can take values from 0 to $(N+K)$. Let T be the random variable representing the total number of packets that are forwarded from all *OXC*$_i$s to the *FDL OXC*. The minimum value of T is 0, corresponding to the case in which all Z packets leave the switch through the primary outputs with no competition among themselves. The maximum value of T is $(N+K-1)$, corresponding to the case where $Z=N+K$, and all these packets are addressed to the same output port. As only one packet leaves the switch through that port, the remaining $(N+K-1)$ packets, represented by T, are forwarded to the FDLs. The distribution of T, $P(T=t)$, can be determined conditioned on Z as follows:

$$P(T=t)=\sum_{z=t+1}^{Z_L}P(T=t|Z=z)P(Z=z)+\delta[t]P(Z=0). \tag{4}$$

Note that the second term of the equation, $\delta[t]\ P(Z=0)$, corresponds to the situation where there is no packet arrival at the primary outputs, an event with probability $P(Z=0)$, in which case no packets will be forwarded to the FDLs, i.e., $t=0$. The upper limit of the summation, Z_L, represents the maximum value of z that can result in no more than t packets to be forwarded to the FDLs. Since at most N packets can be forwarded to the primary outputs, for a given t, Z_L cannot exceed $(N+t)$. On the other hand, the maximum possible value of Z is $(N+K)$, corresponding to the case where packets arrive on all primary and secondary inputs. Thus, when $t>K$, Z_L is $(N+K)$. Therefore,

$$Z_L=N+\min(t,K). \tag{5}$$

The event $T=t$ implies that out of z packet arrivals at the output ports, (z–t) packets leave the switch through (z–t) output ports while t packets are forwarded to the FDLs due to their contention with the $(z-t)$ packets. The $(z-t)$ output ports through which the (z–t) packets leave the switch are randomly chosen by these packets, as the output ports desired by different packets are independent from each other and uniformly distributed among the N primary output ports. Therefore, these $(z-t)$ ports are selected randomly from the N total output ports in $\binom{N}{z-t}$ different ways, each of which is equally likely. The total number of combinations through which z packets may attempt to leave the switch through N output ports is given by N^z. A subset of these total combinations results in having $(z-t)$ packets leave the switch while t packets are forwarded to the FDLs. To identify the cardinality of this subset, surjective-mapping technique [4] can be utilized.

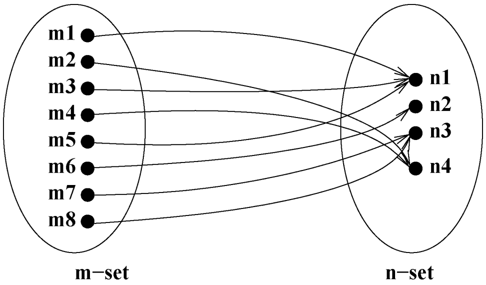

Fig. 2. Surjective mapping from m-set to n-set.

Surjective mapping provides the number of different ways, $S_{m,n}$, to map an m source set to an n destination set such that every element of the destination n-set elements is mapped to by at least one element of the source m-set elements. For example, Fig. 2 shows a source m-set and a destination n-set with $m=8$ and $n=4$. Each element of the four elemets in the n-set is mapped to by at least one element of the eight elements from the m-set. In the optical switch under consideration, the $(z-t)$ output ports correspond to the destination n-set while the z packet arrivals correspond to the source m-set. The idea here is to surjectively map z packet arrivals to $(z-t)$ output ports. Since each output port can only serve one packet in a time slot, in case more than one packet is addressed to an output port, one packet will be served by that port while the rest are forwarded to the FDLs. This mapping implies that there will be competition among the z packets since $z\geq z-t$. As such, $(z-t)$ packets leave the switch through the $(z-t)$ output ports while t packets are forwarded to the FDLs. The formula to identify the number of ways to surjectively map z packets to $(z-t)$ output ports, $S_{z,z-t}$, is given by [4]

$$S_{z,z-t}=\sum_{i=0}^{z-t}(-1)^{i}\binom{z-t}{i}(z-t-i)^{z}. \tag{6}$$

The cardinality of the subset that results in t packets getting forwarded to the FDLs can therefore be identified by multiplying the number of $(z-t)$ output ports that can be randomly selected from the N total output ports, $\binom{N}{z-t}$, by the number of ways to surjectively map z packets to (z–t) output ports, $S_{z,z-t}$. Therefore, for a given number of packet arrivals at the primary outputs, z, the probability of having t packets getting forwarded to the FDLs can be found by dividing the cardinality of the subset that results in t packets getting forwarded to the FDLs, which is $\binom{N}{z-t}S_{z,z-t}$, by the total number of ways z packets attempt to leave the switch through the N output ports, which is equal to N^z. Therefore,

$$P(T=t|Z=z)=\frac{\binom{N}{z-t}S_{z,z-t}}{N^z}. \tag{7}$$

Therefore, from (3) and (7), the distribution of T ((4)) can be rewritten as

$$P(T=t)=\sum_{z=t+1}^{Z_L}\frac{\binom{N}{z-t}S_{z,z-t}}{N^z}\sum_{x=0}^{z}P(X=x) \cdot P(Y=z-x)+\delta[t]P(Z=0). \tag{8}$$

The random variable X corresponding to the number of packet arrivals at the secondary inputs is equal to T except in the case when $T\geq K$, for which X is equal to K. The distribution of X is given by

$$P(X=x)=\begin{cases}P(T=x), & \text{if } x<K\\ \sum\limits_{j=K}^{N+K-1}P(T=j), & \text{if } x=K.\end{cases} \tag{9}$$

By using the distribution of X [(9)], the distribution of T [(8)] can be evaluated using matrix inversion.

The mean number of packets that enter the switch in a given time slot, $E[Y]$, is the mean of the binomial distribution associated with the random variable, Y, and hence,

$$E[Y]=N\rho. \tag{10}$$

The mean number of packets that are dropped in a time slot, $E[\Phi]$, is the mean number of packets represented by T that exceeds the number of FDLs, K, and hence,

$$E[\Phi]=\sum_{t=K+1}^{N+K-1}(t-K)P(T=t). \tag{11}$$

Thus, the probability of blocking of the switch, P_B, is the ratio of the mean number of packets that are dropped to the mean number of packets that enter the switch in a given time slot. Thus,

$$P_B=\frac{E[\Phi]}{E[Y]}=\frac{1}{N\rho}\sum_{t=K+1}^{N+K-1}(t-K)P(T=t). \tag{12}$$

The utilization of the FDLs is load dependent. This parameter helps identify the suitable number of FDLs when designing optical shared-buffer switch. Let the fraction of FDLs that is utilized in a given time slot be U: U is (t/K) when $t\leq K$ and 1 when $t>K$. The FDL utilization is therefore

$$U=\frac{1}{K}\sum_{t=0}^{K}tP(T=t)+\sum_{t=K+1}^{N+K-1}P(T=t). \tag{13}$$

Let the probability that a packet recirculates the switch during a given time slot be ξ. It is the ratio of the number of packets that recirculate the switch to the total number of packets attempting to leave the switch, which is represented by the random variable Z. The number of packets that recirculate the switch is equal to t when $t\leq K$, and equal to K when $t>K$. Therefore,

$$\xi=\sum_{t=1}^{K}\sum_{z=t+1}^{N+t}\frac{t}{z}P(T=t|Z=z)P(Z=z) +\sum_{t=K+1}^{N+K-1}\sum_{z=t+1}^{N+t}\frac{K}{z}P(T=t|Z=z)P(Z=z). \tag{14}$$

Let D be the random variable representing the delay, in terms of the number of time slots, a packet spends due to recirculating in the switch. Note that for delay evaluation, we consider only the packets that eventually leave the switch, as opposed to the packets that are dropped. Therefore, the delay distribution is to be conditioned on the fact that the packets under consideration eventually leaves the switch.

Let Ψ represent the event that a packet eventually leaves the switch. Thus, the distribution of the delay the packets encounter may be expressed as $P(D=d|\Psi)$, and hence,

$$P(D=d|\Psi)=\frac{P(\{D=d\}\cap\Psi)}{P(\Psi)}. \tag{15}$$

Let the probability that a packet among z packets leaves the switch be σ. This probability is the ratio of the number of packets that leave the switch, $(z-t)$, to the total number of packets attempting to leave the switch, z. Therefore,

$$\sigma=\sum_{t=0}^{N+K-1}\sum_{z=t+1}^{N+t}\frac{(z-t)}{z}P(T=t|Z=z)P(Z=z). \tag{16}$$

The probability $P(\Psi)$ can be found by considering all possible number of recirculations a packet might experience after which it leaves the switch. Therefore,

$$P(\Psi)=\sum_{d=0}^{\infty}\xi^d\sigma=\frac{\sigma}{1-\xi}. \tag{17}$$

Now, $P(\{D=d\}\cap\Psi)$ is the probability that a packet encounters d recirculations after which it leaves the switch. Therefore, this probability can be written as

$$P(\{D=d\}\cap\Psi)=\xi^d\sigma. \tag{18}$$

Therefore, (15), can be written as

$$P(D=d|\Psi)=\frac{\xi^d\sigma}{P(\Psi)}=\xi^d(1-\xi). \tag{19}$$

Note that, the number of recirculations a packet experiences in the switch follows a Geometric distribution whose parameter is ξ. This delay distribution is only for those delivered packets, i.e., the dropped packets are excluded. Each packet among the z packet arrivals is equally likely to be forwarded to the FDLs, i.e., independent of how many recirculations a packet has experienced in the switch so far. Therefore, the number of encountered recirculations a packet experiences follows geometric distribution. The average delay a packet encounters in the switch is, therefore,

$$\bar{D}=\frac{\xi}{1-\xi}. \tag{20}$$

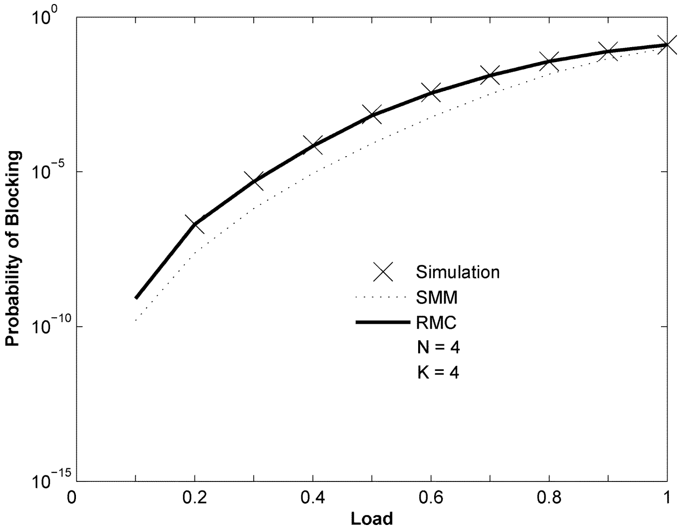

Fig. 3. Loss probabilities from the RMC based model [1], from the SMM based model, and from the simulation model for $N = K = 4$.

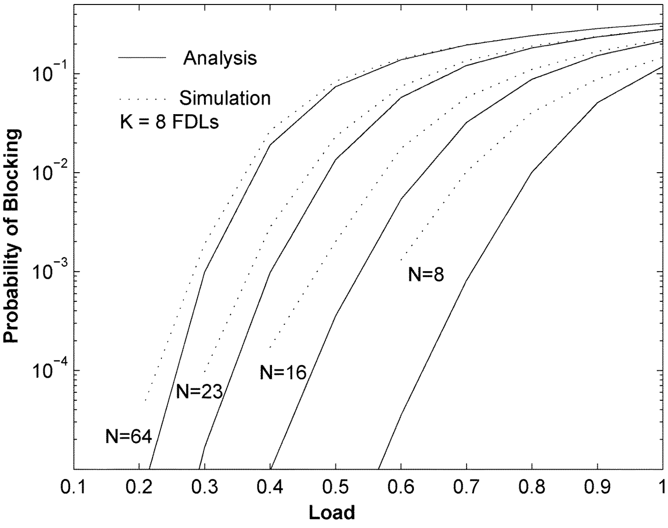

Fig. 4. Loss probability of optical shared-buffer switch with different nodal degrees at different loads.

For a given switch configuration, it would be useful to identify the delay, in terms of the number of recirculations, most of the packets encounter in the switch. Let D_U be the amount of recirculations that makes $P(D > D_U) < \epsilon$. From the *CDF* of the delay distribution

$$D_U = \left\lceil \frac{Ln(\epsilon)}{Ln(\xi)} - 1 \right\rceil. \tag{21}$$

IV. RESULTS

The results from analytical and simulation models for the slotted optical shared-buffer switch are presented in this section. A simulator was developed to evaluate the performance of optical shared-buffer switches with feedback FDLs [7]. In every time slot, the traffic is randomly generated at the primary inputs, with destinations (*iid*) uniformly distributed among the output ports. In the simulator, a packet forwarded to the FDLs maintains its initially assigned destination. In case of competition, the preferred output port is given randomly to one of the competing packets from either the primary or secondary inputs, while the rest of the competing packets are forwarded to the FDLs. The results are not calculated until the steady state is reached as indicated by loss probability. The steady state was determined by sampling results after gaps of 10 000 processed packets. The number of packets processed to reach steady state varied from a simulation run to a simulation run.

Fig. 3 compares the blocking probability values for a 4 × 4 switches with four FDLs based on RMC model, presented in [1], with those from SMM based model. Results from the simulation for the same switch are also shown in the figure. The SMM based results show a good match to that of RMC based model. Yet, the latter approach is limited to switches with small nodal degrees, whereas the proposed SMM based model, provides a feasible method to model optical switches with high nodal degree augmented with any number of FDLs.

Fig. 4 shows analytical results for probability of blocking, calculated using (12) as well as simulation based results, for 8 × 8, 16 × 16, 32 × 32, and 64 × 64 optical shared-buffer switches, each of which is augmented with eight FDLs. Note that as the number of FDLs (K) approaches the number of primary inputs N, as in the case of 8 × 8 optical shared-buffer switch with eight FDLs, the analytical results differ from those of the simulation. This is due to the approximation that, at each time slot, the number of packets arriving at the secondary inputs are assumed to be independent and identical distributed (*iid*) random variables, each of which is thus represented by the random variable X. In fact, in a given time slot, the number of packets arriving at the secondary inputs depends on the number of packet arrivals at these inputs in the previous time slots. Similarly, the destinations of packets arriving at the secondary inputs in a given time slot are assumed to be independent of packets arriving at both primary and secondary inputs in the previous time slots. The difference between the analytical and the simulation results shown in Fig. 6 can be attributed to this approximation. This approximation also explains the discrepancy between results from both SMM and RMC based models shown in Fig. 3, which depicts results for the case where N and K are equal. Nevertheless, these dependencies becomes marginal as N moderately exceeds K. That is due to the fact that, as the number of primary inputs (N) becomes moderately higher than the number of the secondary inputs (K), the number of packets entering the FDLs is dominated by packet arrivals from the primary inputs and hence the dependency between packet arrivals from the FDLs in successive time slots is marginal. From a practical perspective, it is reasonable to assume K to be significantly less than N due to high hardware complexity required for the switch implementation as more FDLs are employed. Furthermore, as shown in Fig. 5, the performance enhancement, in terms of the probability of blocking, achievable by employing more FDLs diminishes with K for a value of K significantly less that N. The case where $N = 64$ and $K = 8$ in Fig. 4 reinforces the fact of the marginal dependency between packet arrivals from the FDLs in successive time slots as N becomes larger than K. Therefore, in such cases, when N is larger than K, SMM based model provides more accurate results as these results very closely match the simulation results.

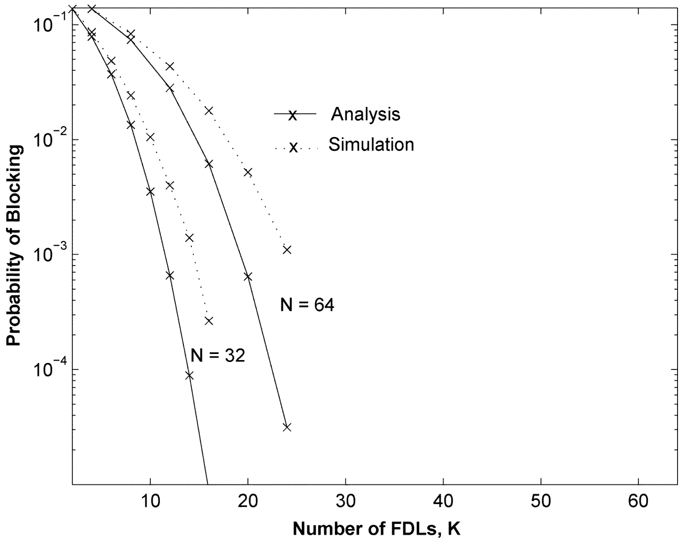

Fig. 5. Variation of the loss probability of optical shared-buffer switch with the number of FDLs at 50% load.

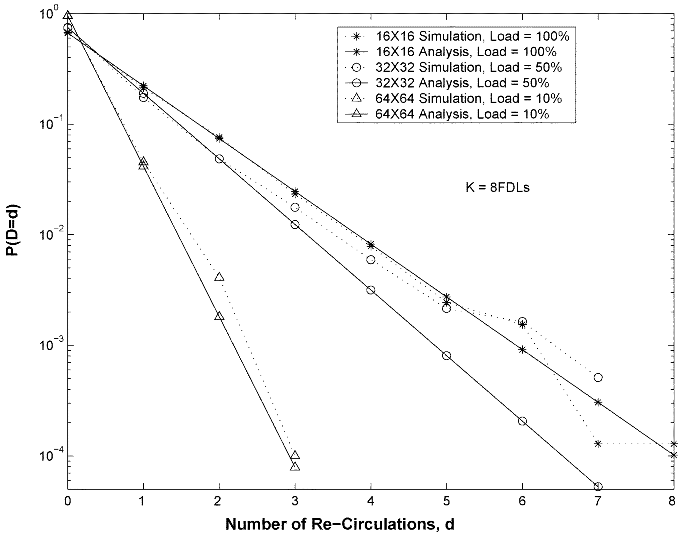

Fig. 6. Delay distribution of delivered packets.

Fig. 6 shows the delay distributions of both the analytical model, generated using (14) and (19), and the simulation model for 16×16, 32×32, and 64×64 optical shared-buffer switches, each of which is augmented with eight FDLs, at loads of 100%, 50%, and 10%, respectively.

Fig. 7 shows the average delays a packet encounters, calculated using (20), in 16×16, 32×32, and 64×64 optical shared-buffer switches, each of which is augmented with eight FDLs. The average delay reveals an increasing trend up to a certain load after which it decreases. This decrease in the average delay is due to the higher probability of blocking that takes place at higher load values at which the chance a packet recirculating in the switch becomes smaller.

Fig. 8 shows the average delay a packet encounters in 16×16, 32×32, and 64×64 optical shared-buffer switches, each of which is augmented with different number of FDLs at 50% load. The average delay curves saturate after certain values of the number of FDLs. This behavior is due to the fact that, for a given load, a certain number of FDLs is enough to handle 100% of the packet arrivals. Beyond this number of FDLs, employing more FDLs does no longer impact on the performance in terms of the average delay.

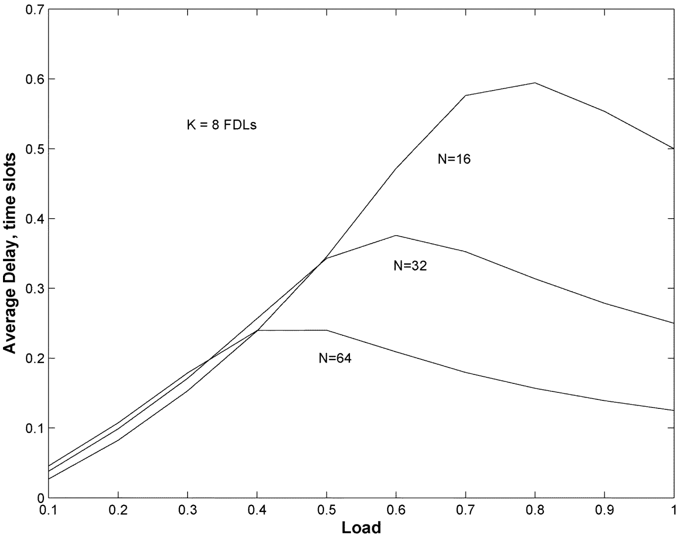

Fig. 7. Average delay for delivered packets at different loads and switch sizes.

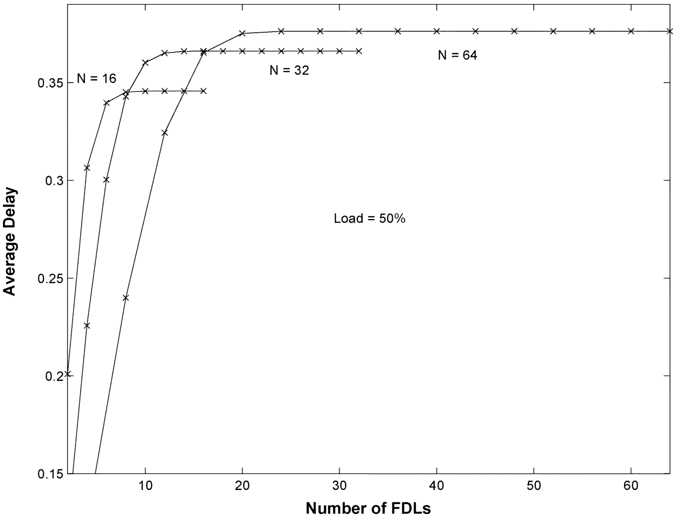

Fig. 8. Average delay a packet encounters versus the number of FDLs for different nodal degrees at load of 50%.

Fig. 9 expresses a similar trend to that revealed in Fig. 7. Fig. 9 shows the probability of a packet recirculating in the switch, generated using (14). The decreasing trend at higher loads may be attributed to the higher probability of blocking associated with the higher loads.

Fig. 10 shows the FDL utilization calculated using (13) for the optical switch with different nodal degrees, and $K = 8$ FDLs. The figure shows that for a given number of FDLs, the higher the nodal degree, the higher is the utilization of FDLs. As the nodal degree of the switch increases, utilization reaches 100% at lower loads.

V. CONCLUSION

We developed a Surjective-Mapping based Model (SMM) to evaluate the performance of slotted optical shared-buffer

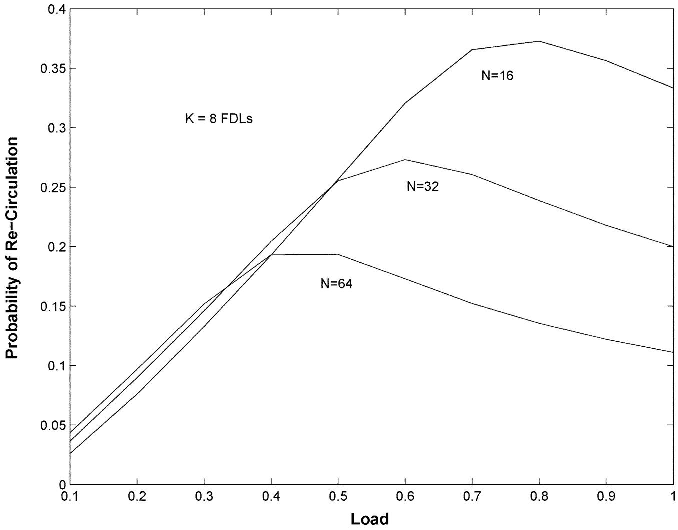

Fig. 9. Probability of packet recirculations versus load for different nodal degrees and eight FDLs.

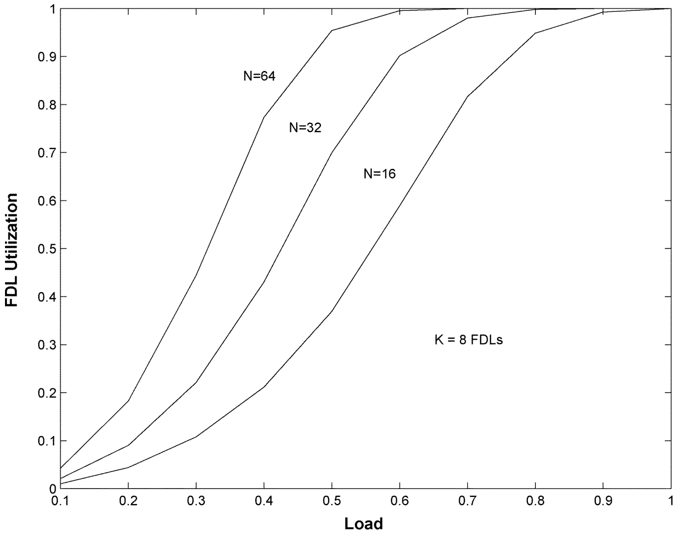

Fig. 10. FDL utilization of the eight FDLs for optical shared-buffer switch with different nodal degrees.

switches utilizing feedback fiber delay lines for optical buffering. The model is especially useful for performance evaluation of switches for which Markovian based models become very complicated. The SMM approach requires significantly less computations, $O(N+K)$, compared to Markovian based models. The model can thus be used to solve large switches for which RMC based approach becomes untractable. Moreover, the model presented in this paper provides a comprehensive insight into the performance characteristics of the switch. The SMM technique realized in this paper is a new approach that can further be utilized to evaluate different slotted communication systems.

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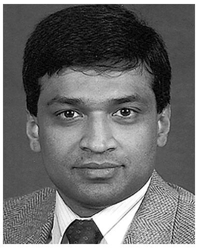

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