Performance Analysis of Multi-Fiber Synchronous Photonic Share-per-link Packet Switches

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Abstract

A performance model is presented for an optical packet switch architecture in which the wavelength converters are shared per output link and each output link consists of multiple fibers. Symmetry of the switch is exploited to derive the packet loss probability for the case where traffic is destined to different output ports with equal probability. The architecture performance is evaluated by means of an analytical model and confirmed by simulations under different switch parameter configurations. Wavelength converters are shown to improve the packet loss probability of the switch. The study shows that synchronous switches equipped with full conversion would have the least conversion utilization rate indicating that the use of a switch with less converter count, i.e., partial conversion, would offer better switch resources utilization and comparable packet loss performance.

1. Introduction

The necessity for a huge bandwidth and transparent high speed data transmission has been triggered by the explosive growth in the Internet traffic. All-optical network employing wavelength division multiplexing (WDM) as multiplexing technology emerges as an innovative solution for the growing traffic explosion problem. WDM technology divides the optical spectrum into a number of non-overlapping wavelengths. Each wavelength is considered as a single communication channel operating at its peak electronic speed [4, 12, 14]. In all-optical networks, the data streams that flow between a source-destination pair remains in the optical domain throughout their paths except at the end nodes, providing transparency with respect to data format. The multiplexing technology provided by WDM introduces the means of effectively utilizing fiber bandwidth [2].

Using the conventional circuit-switched networks (wavelength-routed network), where a connection (light-path) between source-destination pair is established on top of the WDM multiplexing technology before data transmission begins, will result in ineffective use of the bandwidth provided by such technology [8]. To overcome this inherent poor utilization of the WDM channels in wavelength-routed networks, optical packet switching (OPS), which allows fast allocation of wavelengths on demand, is introduced. OPS suffers from the packet contention problem that arises when two or more of the incoming packets on the same wavelength intend to leave the switch through the same output port, which results in packet loss and poor network performance. The contention resolution schemes in optical switches could be implemented in time dimension [9, 11], in space dimension [6], or in both at the same time.

Wavelength conversion (WC) [7] is an example of frequency dimension contention resolution techniques. In this scheme multiple wavelengths are utilized to resolve the contention. The contention could be cleared by shifting all but one of the contending packets to unused wavelengths on the requested output link. The wavelength translation of packets takes place by utilizing a wavelength converter. Using wavelength conversion (WC) with OPS reduces the packets loss due the contentions. Furthermore, WCs are used to eliminate the severity of *wavelength continuity constraint* [5], and improve wavelength agility for dynamic reallocation of optical channels, which in turn enhances the performance and scalability of the network.

The load correlation among wavelengths was considered in [13] with a fixed-alternate routing algorithm. The analytical model in [13] is computationally complex, although its accuracy is limited especially for large networks. Wavelength conversion device is an expensive element [3], thus the number of converters could be considered as the critical cost parameter in OPS design. As such, in this paper we presented results for an optical packet switch with a limited number of converters per output.

In this paper, we study synchronous OPS with limited number of converters that are shared between all wave-

Proceedings of the IEEE Conference on Local Computer Networks 30th Anniversary (LCN'05)
0-7695-2421-4/05 $20.00 © 2005 IEEE

lengths on a specific output link (Share-per-Link WCS). The blocking probability of the switch is used as a metric for switch performance. We evaluate the conversion bank utilization which could be used as an indictor of the number of converters that are needed.

Section II presents different conversion options and the forwarding algorithm that is considered in this work for share-per-link. The analytical model is presented in Section III. Section IV presents performance results, based on both analytical and simulation models, for the optical packet switch employing shared-per-link conversion resources with different configurations. Finally, Section V provides the conclusions.

2. Wavelength Conversion Options

Sharing a limited number of conversion devices is an effective paradigm for the cost reduction of the OPS. Previous studies show that a limited number of conversion devices in an all-optical network could achieve almost the same network performance as when each outgoing wavelength has a dedicated converter. Converter sharing [1, 4, 12] has led the way for a new generation of wavelength routers, called wavelength convertible switches (WCSs). Different types of WCS architectures employing different WC sharing schemes have been introduced in [11]: dedicated WCS, Share-per-node WCS, and Share-per-link WCS.

The dedicated WCS offers a wavelength converter for each outgoing wavelength allowing any incoming wavelength to be switched to the desired wavelength on the desired link [11]. The dedicated WCS is the least cost efficient and most flexible architecture. In the Share-per-node WCS the converters are located in one conversion bank, which is shared among all outgoing links. The conversion bank can be used by any channel on any link [11]. Share-per-link WCS offers each outgoing link a dedicated collection of converters that can only be used by channels on that specific link as shown in Figure 1 [11]. For increased performance and reduced hardware cost, wavelength routing protocols are responsible for better utilization of conversion resources where converters are not dedicated to individual channels. In all of these architectures, sharing efficiency of wavelength converters is inversely related to the hardware complexity of the optical switch. Share-per-link WCS provides a significant cost reduction with comparable performance to share-per-node and dedicated WCS. The conversion resources allocation algorithm that is adopted by the control plane in the share-per-link WCS affects the switch blocking performance. Different conversion resource allocation algorithms and their effects on the end-to-end performance with fixed routing are investigated in [10]. A poor conversion resources allocation is a factor that could lead to poor switch performance due to a higher rate of blocked traffic. A WCS with shared contention resolution resources is the best candidate to reduce hardware volume and cost of all-optical networks. It has been shown that switches with a bank of completely shared wavelength converters, WCs, require a fraction of WCs compared to switch architectures that use a WC per wavelength. The work in [8] has investigated the differences in conversion requirement between the synchronous and the asynchronous switches but has not explored the effects of using multi-fiber switches in concurrence with conversion sharing. In this paper, we develop an analytical model and investigate the performance of the multi-fiber share-per-link slotted OPS. The improvements of key performance metrics such as blocking performance and conversion resource utilization are investigated.

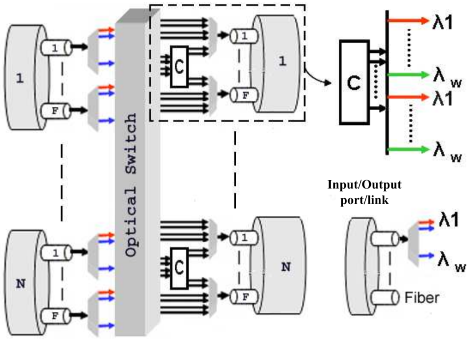

Figure 1. Multi-fiber Synchronous OPS Employing Share-per-link Conversion Resources

3. Analytical Model

A symmetric OPS employing share-per-link conversion resources with *N* inputs, coming from different sources, and destined to *N* outputs links (ports), each consisting of *F* parallel fibers as shown in Figure 1, is considered. The switch supports a *WDM* signal with *w* wavelengths per fiber. A total of *wF* output wavelengths share a conversion bank of *C* converters. A slotted system is considered where the incoming packets are synchronized at the inputs before they are processed. The packet length is assumed to be one time slot. All the traffic is equally likely to be destined to any output port. The following notation is used:

N: Number of Inputs/Outputs of the switch

F: Number of fibers per output

w: Number of wavelengths per fiber

C: Number of converters shared per output link

X_i: Random variable representing the number of packets destained to the output that arrive on λ_i in a slot time, where $i = 1, ..., w$

Y_i: Random variable representing the number of packet that are forwarded for conversion from λ_i

N_Y: Random variable representing the number of input wavelengths that compete for conversion

G_i: Random variable that represents number of free λ_i

B: Random variable representing the total number of free wavelengths on the outputs prior to allocating outputs of converters

$E\{d\}$: Expected number of packets lost

T: Random variable representing the total number of packets forwarded for conversion

A: Random variable representing packets utilizing the conversion bank

$E\{\xi\}$:The expected number of the total packet arrivals to the output

The symmetrical behavior of outputs link allows us to build the model around one output port, where each output link is destined to one specific destination. We consider one output link and its corresponding incoming traffic requests from the input side to study the performance behavior of that port and generalize its performance to all other ports in the switch, since the condition of symmetry holds in this architecture.

X_i packets arrive on λ_i competing for an output in a given time slot. There are *NF* fibers on the input side and hence *NF* incoming channels each at λ_i; so the maximum value that could be taken by X_i is *NF*. The packet is expected to switch from the input port to the output port, which is connected to destination. A packet competes for the same wavelength it arrived on in any of the outgoing fibers. This means that packets arriving at the inputs on λ_i are competing for the same wavelength, λ_i, on the output under consideration. The minimum value of X_i is *zero*, which means that there is no arrival on λ_i at the inputs or none of the arrived packets on λ_i are destined to that specific output link. The probability that a packet arrives at an input port on a given wavelength (λ_i) in a given time slot is denoted by ρ, which corresponds to the normalized offered load. Packet arrivals per wavelength at different inputs are independent of each other. Also the number of packet arrivals on different wavelengths are independently and identically distributed; $\{X_i\}_{i=0}^{w}$ is *iid*. The number of packets competing for an output per wavelength in a given time slot and destined to the output link under consideration follows the binomial distribution for *x=0...NF*, i.e.,

$$P(X_i = x) = \binom{NF}{x} \cdot \left(\frac{\rho}{N}\right)^{x} \cdot \left(1 - \frac{\rho}{N}\right)^{N \cdot F - x} \tag{1}$$

For a given time slot, if the number of arrivals per wavelength that are destined to the considered output is more than *F* packets, contention among them will occur. *F* packets out of the contending ones leave the switch directly using wavelength of interest (λ_i), one on each fiber. Note that direct refers to packets that are directly routed from inputs to outputs without going through converters. The rest of these packets are forwarded to the conversion bank that belongs to the output port under consideration. Let Y_i be the random variable representing the number of packet that are forwarded to the conversion bank on λ_i. When $X_i \leq F$, $Y_i = 0$ and when $X_i > F$, Y_i varies between *one* and *F(N-1)*. It is equal to *one* when X_i, total number of arrivals per λ_i, is equal to *F+1*. If all arrivals at all inputs on λ_i are destined to the same output link, *NF* packets, Y_i will equal to *NF-F*, since *F* of them will leave the switch directly. So the probability that Y_i packets are forwarded to conversion bank from a single wavelength (λ_i) can be derived as follows:

$$P\left(Y_i = y | X_i > F\right) = \frac{P\left(Y_i = y \bigcap X_i > F\right)}{P\left(X_i > F\right)} \tag{2}$$

$$P\left(Y_i = y | X_i > F\right) = \binom{NF}{y+F} \cdot \left(\frac{\rho}{N}\right)^{y+F} \cdot \frac{\left(1 - \frac{\rho}{N}\right)^{NF-y-F}}{1 - \sum_{j=0}^{F} P(X_i = j)} \tag{3}$$

The number of packets Y_i that were not served by the requested wavelength (λ_i) and forwarded to conversion bank is identically independently distributed. Let N_Y be a random variable representing the number of wavelengths that are competing for conversion resources. N_Y could take any value between *zero* to *w*. When N_Y is equal to *zero*, it means that all arrived packets on all wavelengths leave the switch without any conversion, or none of the arrivals are destined to output port under consideration. If each and every wavelength on the output had received more than *F* packets, then N_Y is equal to *w*. So the distribution of N_Y for $n_y = 0...w$ is as follows:

$$P\left(N_Y = n_y\right) = \binom{w}{n_y} \left(\sum_{i=F+1}^{N \cdot F} P(X = i)\right)^{n_y} \cdot \left(\sum_{i=0}^{F} P(X = i)\right)^{w - n_y} \tag{4}$$

Conditioned on N_Y, λ_i is available on the output link if the number of arrivals per λ_i is less than *F* packets per time slot, so these free $\lambda_i s$ need to be considered as available wavelengths that can be used to convert the contending packets to. For a given X_i, we define G_i as a random variable that represents number of free λ_i out of the *F* copies on the output port. G_i takes values between *zero* and *F*, where *zero* means that λ_i on all *F* outgoing fibers are used. It implies that this wavelength has *F* arrivals. If G_i equal to *F*, all λ_i on the output link are free and available for the conversion resources. For a given number of arrivals per λ_i, we can calculate the distribution of G_i as follows:

$$P\left(G_i = g | X_i \leq F\right) = \frac{P\left(G_i = g \bigcap X_i \leq F\right)}{P\left(X_i \leq F\right)} \tag{5}$$

$$P\left(G_i = g | X_i \leq F\right) = \frac{P\left(X_i = F - g\right)}{\sum_{j=0}^{F} P(X_i = j)} \tag{6}$$

The number of packets, which can utilize conversion resources and leave the switch, depends on the minimum of the total available wavelengths on all fibers at the output and number of available converters. Since the packet length is fixed, all converters are available at beginning of the time slot. Accordingly, the total number of wavelengths that are available on the output link, after all direct packets are assigned to outgoing wavelengths, has to be found. To find the available wavelengths on the output link for a given N_Y, we define *B* as the random variable representing the total number of wavelengths free of direct packets (i.e. not routed through converters) on the output link under consideration at any given time slot. The random variable *B* is simply the sum of the random variable G_i, which represents the number of fibers in the port that have no direct packet on λ_i:

$$B = \sum_{i=0}^{w} (G_i) \tag{7}$$

The random variable *B* could take any value between *zero* and $F(w - n_y)$. *B* is equal to *zero* means every outgoing wavelength has at least *F* arrivals. In this case, all packets to the conversion bank are lost as no free wavelength is available on the output port. In contrast, *B* equals $F(w - n_y)$ when there are n_y wavelengths on the output, each having more than *F* arrivals, where the remaining $w - n_y$ wavelengths have *zero* arrivals. Therefore, for a given N_Y, the distribution of *B* is given by:

$$P\left(B = \beta | N_Y = n_y\right) = \begin{cases} 0 & n_y = w \\ \frac{d^\beta}{dz^\beta} H_B(z)|_{z=0} & \text{otherwise} \end{cases} \tag{8}$$

where, $H_B(z)$ is the probability generating function of B.

Packet loss takes place when all $\lambda_i s$ are busy on all *F* outgoing fibers and the total number of packets forwarded to the conversion bank is greater than the minimum number of available converters and free wavelengths on the output. On the other hand, some of the rejected packets from direct connection can be served by utilizing the available wavelengths and leave the switch by getting converted to one of the available channels on the output, provided there are free $\lambda_i s$ on the output port under consideration. The blocking probability of the switch, P_b, is then defined as the ratio of expected number of packets lost, $E\{d\}$, to the total number of arrivals to the output port, $E\{\xi\}$:

$$P_b = E\{d\}/E\{\xi\} \tag{9}$$

The number of packets lost per time slot is equal to the difference between the total number of packets that need conversion and those that left the switch after utilizing converters from the conversion bank. For a given N_Y, the total number of packets that are directed to the conversion bank is equal to the summation of all rejected packets from all busy wavelengths. So, the maximum number of packets that can compete on $min(C, \beta)$ are $[n_y \cdot (NF - F)]$ and the minimum is n_y, where every wavelength considered in n_y has *F+1* arrivals. Let *T* be a random variable representing the total number of packets forwarded to the conversion bank. It can be obtained by the convolution of $Y_i s$ where $i = 1...n_y$, i.e.,

$$T|_{n_y} = \sum_{i=1}^{n_y} (Y_i) \tag{10}$$

For a given n_y, the probability of having $T = \alpha$, which takes values from n_y to $[n_y \cdot (NF - F)]$, packets competing on $min(C, \beta)$ is given by:

$$P\left(T = \alpha | N_Y = n_y\right) = P(\sum_{i=1}^{n_y} (Y_i) = \alpha) \tag{11}$$

Now the distribution of *T* for a given N_Y can be found as follows:

$$P(T = \alpha | N_Y = n_y) = \frac{d^\alpha}{dz^\alpha} \cdot H_T(z)|_{z=0} \tag{12}$$

where, $H_T(z)$ is the probability generating function of T.

For a given n_y, the average numbers of packets forwarded to the conversion bank, $E\{T\}$, is equal to the summation of the average of individual $Y_i s$, which is given by:

$$E\{T | N_Y = n_y\} = n_y \cdot E\{Y\} \tag{13}$$

In general, $E\{T\}$ can be calculated by taking the summation over all possible values of N_Y, which is given by:

$$E\{T\} = \sum_{n_y=0}^{w} P(N_Y = n_y) \cdot (n_y \cdot E\{Y\}) \tag{14}$$

The average number of packets that are forwarded to the conversion bank per wavelength, $E\{Y\}$, is given by:

$$E\{Y\} = \sum_{j=1}^{N \cdot F - F} (j \cdot P(Y = j)) \tag{15}$$

To calculate the number of the packets that can utilize the converters and leave the switch, we define a new random variable *A* to represent those packets, which utilize the conversion bank. In a time slot, if total number of $Y_i s$, n_y, is less than or equal to $min(C, \beta)$ and $\alpha \leq min(C, \beta)$, which is the total number of packets forwarded to the conversion bank, then $A = T$, which means that all the packets forwarded to the conversion bank will utilize the conversion resource and leave the switch without any loss. Accordingly, the average number of lost packets, $E\{d\}$, equals *zero*. On other hand, if $n_y > min(C, \beta)$ or $\alpha > min(C, \beta)$ only $min(C, \beta)$ packets can leave the switch through wavelength converters while the rest will be lost. So for a given n_y and β, *A* is defined as:

$$A = \begin{cases} \text{T, if } n_y \leq min(C, \beta) \; and \, T \leq min(C, \beta) \\ min(C, \beta), \text{otherwise} \end{cases} \tag{16}$$

For a given n_y and β, the average number of packets that will utilize the conversion resources and leave the switch, $E\{A|N_Y = n_y, B = \beta\}$ can be calculated as follows:

$$E\{A|_{n_y,\beta}\} = \begin{cases} min(C, \beta), \text{ if } min(C, \beta) < n_y \\ \\ \sum_{j=n_y}^{min(C,\beta)} (j \cdot P(T = j)) + min(C, \beta) \cdot \\ (\sum_{j=min(C,\beta)+1}^{n_y(F(n-1))} P(T = j)), \text{ otherwise} \end{cases} \tag{17}$$

From equation 17, if $n_y > min(C, \beta)$, the average number of packets that can be converted is equal to $min(C, \beta)$, and the remaining packets will be dropped. On the other and, if n_y is less than or equal to $min(C, \beta)$, the arrived packets at the conversion bank are converted, as long as their number is less than or equal to $min(C, \beta)$. Other wise, only $min(C, \beta)$ packets, out of those arrivals, are converted. Since the maximum numbers of packets that can utilize the conversion and leave the switch is dependent on the $min(C, \beta)$, the average number of packets that will utilize the conversion resources and leave the switch, $E\{A\}$, can be calculated by taking the summation over all possible values of N_Y and *B* and given as follows:

$$E\{A\} = \sum_{n_y=1}^{w} (P(N_Y = n_y) \sum_{\beta=0}^{(w-n_y)F} P(B = \beta) \cdot (E\{A|N_Y = n_y, B = \beta\})) \tag{18}$$

Now we can calculate the average number of packets that will be dropped, $E\{d\}$, as the difference between the average of total forwarded packets to conversion bank, $E\{T\}$, and the average accepted packets for conversion, $E\{A\}$, and given by:

$$E\{d\} = E\{T\} - E\{A\} \tag{19}$$

The average number of packet arrivals per wavelength on the output under consideration is equal to $F \cdot \rho$. So, the total expected arrival to the output link, shown in the denominator of equation 9, is given by:

$$E\{\xi\} = w \cdot F \cdot \rho \tag{20}$$

Then the blocking probability can be found using equations 9, 19, and 20. An expression for the conversion bank utilization considering all switch parameters can be derived. The conversion bank utilization is defined as the ratio between the average number of packets that are converted to the total number of the converter devices that are shared among all wavelengths on a single output link. The conversion bank is 100% utilized when $min(C, \beta) \geq C$ while $\alpha \geq C$. This suggests that *C* packets out of *T* leave the switch after getting converted. On the other hand, the conversion bank will be 0% utilized if all contending packets are dropped due the unavailability of wavelength on the output link, ($\beta = 0$), or if all arrived packets, $X_i s$ are less than or equal to *F*, in which case the conversion bank is not needed. Accordingly, the conversion bank utilization is equal the average number of packets leaving the switch, after conversion, over the number of shared converter devices per output link. The utilization is given by:

$$U = E\{A\}/C \tag{21}$$

where $E\{A\}$ is obtained by equation 18. The following section discusses the simulation and the analytical models' results in further detail.

4. Analytical and Simulation Results

A synchronous optical packet switch with a conversion bank share-per-output-link was simulated considering *C*, number of shared converters in the conversion bank, *w*, number of wavelengths per fiber, and *F* parallel fibers per output. For a given packet, if the requested wavelength is not available in any outgoing fiber in the output link, i.e. there are more than *F* packets at the inputs that are destined to λ_i on a time slot, the request will be forwarded to a shared converter bank. If there is not a free converter or if there is a free converter but no wavelength free on the output link, the incoming request will be lost.
The assumptions used in the simulation are:

1. The offered traffic is in the form of connection requests for an entire optical channel. These requests per wavelength arrive at inputs with probability *ρ*.
2. Connection holding time (packet length) is fixed as one time slot.
3. Connection requests that cannot be serviced are lost.
4. The connection requests are uniformly distributed among the wavelengths.

The simulator, written in C++ language, implements a discrete event simulation of node. The node configuration parameters are fed to the simulator as inputs. It has the ability to handle different node parameters such as number of fibers per output link *F*, number of wavelengths per fiber *w*, and different number of shared converters per output link *C*. To get an accurate result from the simulator, the data is not accumulated until the steady state is reached as indicated by the loss probability. The tolerance for testing the steady states is 0.001, i.e., and the simulation runs until the loss probability reach a variation of not more than 0.1%.

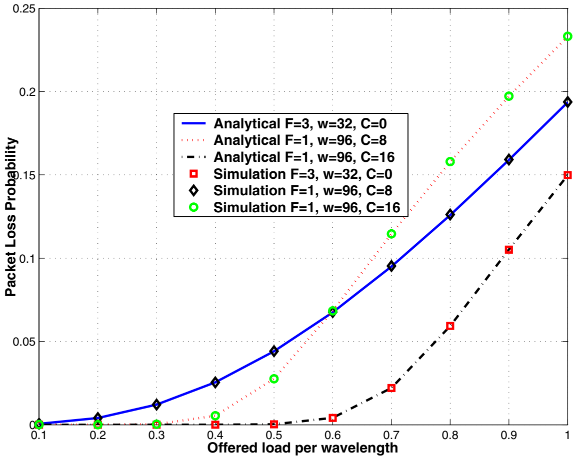

Figure 2. Packet Loss Probability Vs. Load

In Figure 2, the packet loss probability is plotted as a function of offered load per wavelength for 3 differently configured synchronous switches. The results for all figures in this section are obtained at $N = 4$. This figure consistently shows that a single fiber link switch with *w=96* and *C=16* behaves considerably better than a similar switch with less number of shared converters per link, *C=8*. The switch with higher count of shared converters per link offers better packet loss performance due to its ability to accommodate the higher traffic. The figure also shows that a switch with *F=3* and *C=0* performs better at higher loads compared to the *F=1* and *C=8* switch. This indicates that using multiple fiber links in higher offered load regions has a better effect on performance than the converter count even though the number of total wavelengths is the same in both cases. In the case of multiple fibers, dividing the total number of wavelength available into sets of similar wavelengths in each fiber offers a better utilization of wavelength resources and accordingly better packet loss behavior at higher rates of offered loads. At lower offered loads, the effects of shared converter counts in the single fiber case has more influence on utilization than the multi-fiber link case due to role the conversion plays in resolving contention.

In Figure 3, the packet loss probability is plotted as a function of offered load per wavelength for 3 switches for different values for *F* and *w*, with the total wavelenght count, Fw, held constant. This figure presents the enhancement achievable in the packet loss probability as more fibers per output are considered in the case when the total wavelength count in the 3 different cases is the same, the total wavelengths in each case is *w=96*. It also confirms that the simulation results totally substantiate the accuracy of the devolved analytical model. It can be deduced that the number of shared converters can be significantly reduced when using multiple fibers due to the higher utilization the multifiber link offers for the same set of total wavelengths in the system. We considered similar number of shared converters in all of presented case, *C=8*, to emphasize the effect of using multiple fibers. This result offers an opportunity for cost tradeoffs between using multiple fiber links and the shared converter count in the network. These results are more evident in higher offered loads due to the need for better managing the fiber, wavelength, and shared converter resources.

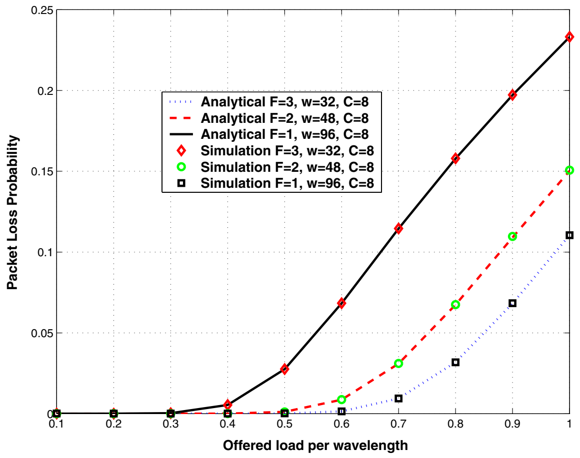

Figure 3. Packet Loss Probability Vs. Load

In Figure 4, the conversion bank utilization is plotted as a function of offered load per wavelength for the same switches considered in Figure 3. This figure shows that output links with fewer fiber counts have higher conversion bank utilization where as switches with higher fiber count in their output links have lower utilization rate for the conversion resources. The opportunity of cost tradeoffs is much clearer in this case where less conversion bank utilization means that the need for conversion is less in the multifiber case when the total number of wavelength is the same. From this, it can be deduced that a the synchronous switch

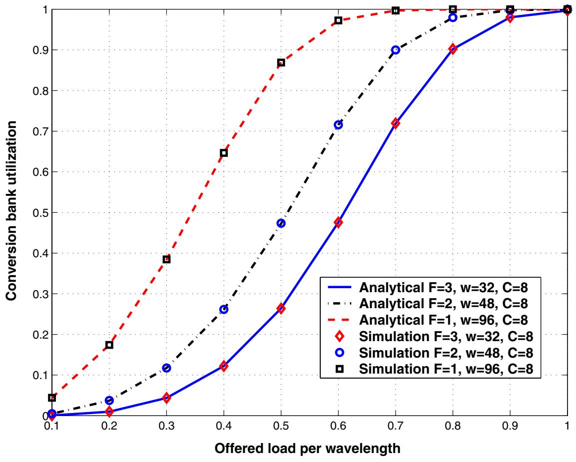

Figure 4. Conversion Bank Utilization Vs. Load

equipped with full conversion would have the least conversion utilization rate indicating that use of a switch with fewer converter count, partial conversion, would offer better switch resources utilization and comparable packet loss behavior.

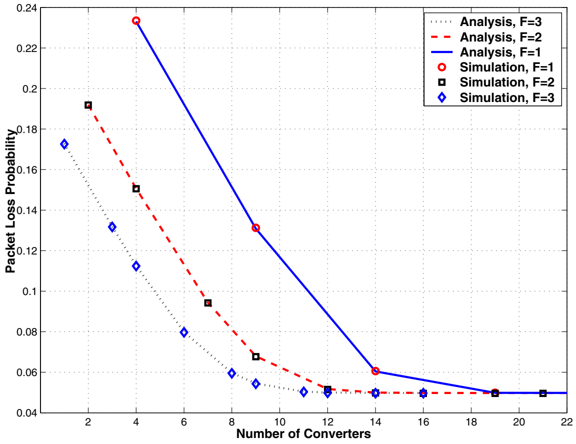

Figure 5. Packet Loss Probability vs. The Number of Converters for $\rho = 1.0$, $F \cdot w = 48$

Figure 5 considers packet loss probability with respect to the number of converters in the shared conversion bank where the offered load per wavelength, ρ is 1.0. The figure considers the same set of *F=1, 2, and 3* for *w=16* per fiber. The packet loss probability decreases with the increase of converter count in the shared conversion bank until a point where the number of converters doesn't make a significant difference. The point where the addition of converters would not improve the packet loss probability depends on the fiber count on the output link. When *F=3*, having more than 12 converters in the shared conversion bank would not improve the performance further This number increases when using less fiber counts in the output link.

In Figure 6, the conversion bank utilization is plotted as a function of number of converters for the same switches discussed in Figure 5. The conversion bank utilization decreases with the increase of converter count in these shared conversion banks. The utilization of the conversion bank is less for the case of multi-fiber link, in which more converters are required. Figures 5 and 6 illustrate the relationship between packet loss probability, conversion bank utilization and the number of shared converters per link. These figures confirm the argument that full wavelength conversion, where each wavelength has its own converter, is considered as the least optimized switch from the point of view of utilization.

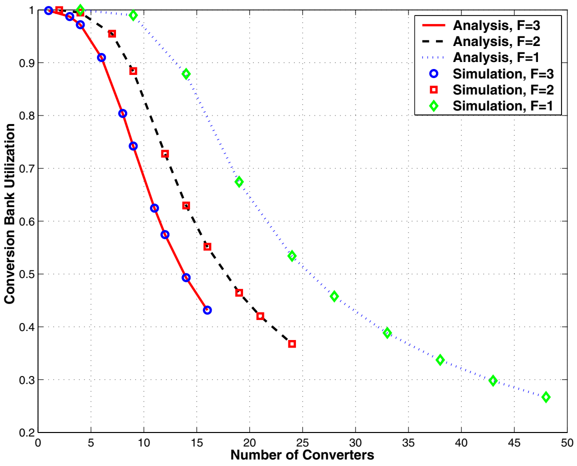

Figure 6. Conversion Bank Utilization vs. The Number of Converters for $\rho = 1.0$, $F \cdot w = 48$

Finally, in Figure 7, the gain is plotted as a function of the offered load. The gain in this figure is the ratio of throughput of the switch with reference to throughput performance of a switch that has *F=1*, *w=96* per fiber, and *C=0* for a link. The objective is to illustrate the use of the model to compare different switch configurations. As expected, the gain, compared to the reference switch, increases when *F=2* and *C=8* when the total number of wavelengths employed by these fibers is the same as the total wavelengths employed in the reference switch configuration. This shows that increasing the fiber count, *F*, has a significant effect on performance, confirming results discussed earlier. If *F=3*, *C=0* and *w=32* per fiber, the figure shows that such switch has

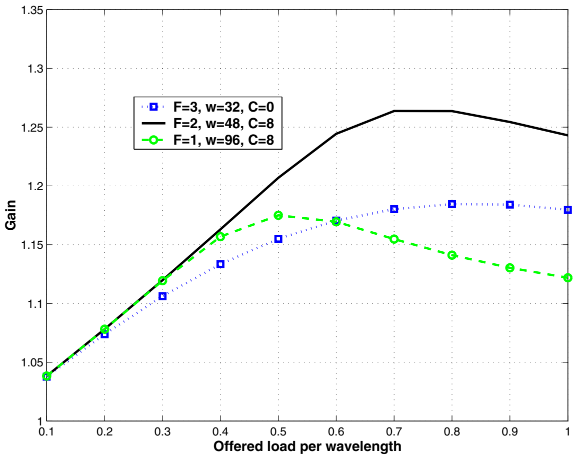

Figure 7. **Performance Gain vs. the Offered Load**

the lowest gain in the region of low offered loads, whereas a switch with *F=1*, *C=8* and *w=96* outperforms the earlier switch in the similar offered load region. In the higher region of offered loads, these two switches behave in an opposite manner.

5. Conclusion

A synchronous optical packet switch with a conversion bank in share-per-output-link configuration was evaluated analytically and by means of computer simulation. These results show very close agreement between results confirming the accuracy of the analysis. Results further showed that at higher offered loads, the switch with higher count of shared converters per link offers better packet loss performance due to its ability to accommodate more traffic. At higher loads, it also showed that, for a given number of wavelengths, using multiple fiber links can be a more attractive option in terms of performance than increasing converter count. At lower offered loads, the effects of shared converter count in the single fiber case is more pronounced on utilization than in the multi-fiber link case due to role the conversion plays in resolving contention. The number of shared converters can be significantly reduced when using multiple fibers due to the improvement due to the higher utilization the multi-fiber link offers. The model offers means for cost performance tradeoffs between using multiple fiber links and the shared converters in the network.

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