Performance Merits of Multi-Fiber DWDM Networks Employing Different Shared Wavelength Conversion Resources Architectures

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Abstract—**The end-to-end performance for circuit switched all-optical networks in multi-fiber multi-hop environments is modeled and evaluated with and without wavelength conversion. We study the effects of parameters such as path length, number of fibers, number of wavelengths in each fiber, and offered load on key performance parameters in multi-fiber multi-hop setting. The increase in performance in the wavelength routing DWDM network due to wavelength conversion at each node, and different degrees of wavelength conversion are considered. This work also examines different wavelength converter sharing architectures and their effects on performance when the hops along the path between source-distention pair have different loads. It also examines the performance issues for share-per-link wavelength convertible switch (WCS) using a simple Conversion Resources Allocation Algorithm (CRAA).**

I. INTRODUCTION

Wavelength routing technologies allow networks to scale in capacity to meet the unprecedented rate of traffic growth. The problem of allocating optical bandwidth in optical networks that utilize Dense Wavelength Division Multiplexing, DWDM, which is used to establish end-to-end all-optical lightpaths to route optical signals between pairs of source-destination nodes in circuit switched networks, is closely tied to the number of distinct wavelengths that are utilizable and the ability to convert wavelengths. DWDM allows an increase in the number and density of packed wavelengths, which have to fit in the spectrum windows at either 1.3 or 1.55 microns, in the same fiber [5]. The entire bandwidth of a wavelength on each link is dedicated to a source-destination pair.

The limited number of wavelengths in the fiber reduces the flexibility in bandwidth allocation and limits the bandwidth granularity for heterogeneous services in Internet traffic. Trying to add more channels into a single fiber using fine spacing techniques reduces the wavelength stability by increasing channel cross-talk in a DWDM network [5]. The significance of using multiple fibers can be seen when considering the number of useable channels, as traffic demand scales, in the conventional C-band window (1535-1565 nm) instead of populating a fiber with W channels, the designer has the option of using $w = \frac{W}{F}$ channels in each of F fibers. The cost effectiveness of this approach due to the fact that an optical fiber cable consists of multiple fibers supports the use of multi-fiber configuration. This also means that the same set of wavelengths is available on each fiber thus providing an added architectural flexibility in the design of switching nodes. We show below that this could result in significant performance advantages.

The absence of wavelength conversion, [3], [16], is another factor that could lead to poor performance of the network due to a higher rate of blocked traffic. A connection request is blocked when a wavelength with sufficient capacity is not found in any intermediate hop between the source-destination pair, even if there is free capacity on different wavelengths, causing inefficient utilization of wavelength resources and results in higher network contention and blocking probability according to the wavelength continuity constraint [14]. The employment of wavelength conversion, which allows for more flexibility in assigning channels to a lightpath, reduces the call blocking probability significantly by reusing the unused wavelengths in the network. It also reduces the size of the crossconnect switch and increases the performance gain for a given utilization delivering scalability, flexibility and lower operating expenses. Wavelength conversion, WC, can be: (1) full-range wavelength conversion, FWC, [16], or (2) limited-range wavelength conversion, LWC, [11], [16]. LWC converts an incoming wavelength to a subset of the full wavelength set. LWC was studied in [13] when the range

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of wavelength conversion is 2-adjacent wavelengths. This work developed a model for the LWC on torus network using a single fiber connection. The routing algorithm also affects the performance of wavelength-routed optical networks. The routing algorithms could be either non-adaptive or adaptive depending on whether it considers the network state at the time of finding the route between specific source-destination pairs. The work in [7] studied the two types of routing algorithm by developing theoretical models that consider the wavelength conversion.

Blocking probability in wavelength-routed optical networks has been studied previously, ex. [3], [11], [16] but only in a single-fiber context. This paper is an extension of our previous work [1] that examined the use of multiple fibers in WDM networks with the assumption that every hop in the path has the same offered load, ρ. Here, we also consider the use of different shared wavelength convertion schemes and compare key performance parameters using a simple Conversion Resources Allocation Algorithm (CRAA). This paper differs from the previous work in that it considers the use of multiple fibers in parallel, with same set of wavelength in each fiber. We also compare networks where every node is connected to its neighbors with multiple fibers that do not have wavelength conversion option to networks that employ multi-fibers with wavelength conversion option using different conversion resources sharing architectures under the assumption of having different offered loads, (ρ_i), in different hops along the path between source-destination pair. The merits of using share-per-link conversion architecture under different CRAAs were considered in [4]. The improvements of key performance metrics such as end-to-end blocking performance and throughput in wavelength routing networks employing multi-fiber multi-hop configurations under different wavelength conversion scenarios are investigated. Analytical models are developed to show the improvement in utilization under various operational scenarios.

This paper is structured as follows. Section 2 presents the wavelength conversion options. Sections 3 and 4 derive the blocking performance of paths for multi fiber link without and with conversion option respectively. Performances of these two cases are discussed in Section 5 and 6 followed by conclusion in Section 7.

II. WAVELENGTH CONVERSION OPTIONS

Wavelength convertible switches (WCS), optical switches (OSW) employing wavelength converters (WC), [3], [17], offer flexible lightpath switching, contention resolution, network interoperability as well as transparency of the optical layer [9], [17]. Important functions of WCS's are that they allow optical networks to be reconfigurable on a wavelength-by-wavelength basis to match changing traffic demands and to restore the network in case of failures [12], [15]. The major categories of WCS are reviewed next.

The *dedicated WCS*, shown in figure 1, offers a wavelength converter for each outgoing wavelength allowing any incoming wavelength to be switched at desired wavelength to the desired link [8]. The dedicated WCS is the least cost efficient and most flexible architecture. More cost effective architectures use different converter sharing mechanisms [6], [10].

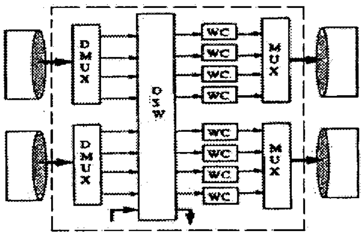

Fig. 1. The dedicated wavelength-convertible switch [8]

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 2 [8]. The use of different CRAAs for share-per-link WCS depicts different performance parameters.

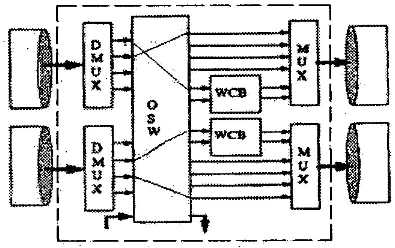

Fig. 2. Share-per-link wavelength-convertible switch[8]

Share-per-node WCS offers all outgoing links a shared collection of converters that can be used by any channel on any link as shown in figure 3 [8]. For increased performance and reduced hardware cost, wavelength routing protocols are responsible for better conservation of conversion resources where converters are not dedicated to individual channels or outgoing links.

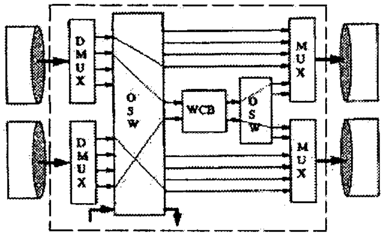

Fig. 3. Share-per-node wavelength-convertible switch[8]

In all of these switch architectures, sharing efficiency of wavelength converters is inversely related to the hardware complexity of the optical switch. Next, we investigate the single-route end-to-end blocking probabilities using these switch architectures in the multi-fiber multi-hop networks.

III. BLOCKING PROBABILITY FOR PATHS WITHOUT WAVELENGTH CONVERSION

Consider a network with mulitple fibers in each hop as shown in figure 4, where node S requests a path session to destination node D over a DWDM optical mesh network. We assume that every call requests a capacity of a full wavelength bandwidth. Any particular fiber along the path has the same set of wavelengths and no two sessions on the same fiber use the same wavelength according to the wavelength continuity constraint. An optical path is set from source to destination by reserving the particular wavelength in all intermediate hops.

In this section, we consider the networks without wavelength conversions. A request is blocked When no common unused wavelength is available in all the hops.We also assume different offered loads ρ_i for each hop along the path between source-destination pair.

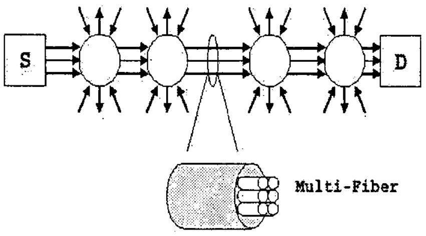

Fig. 4. A multi-fiber multi-hop environment

The blocking probability P for multi-fiber multi-hop network is the probability that each wavelength in every fiber is used on at least one of the intermediate hops, H.

The avilability, A, along the path in the case of multi-fiber no conversion hop is shown in figure 5.

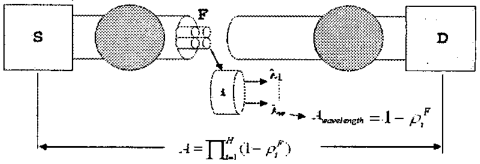

Fig. 5. End-to-end multi-fiber link

P is thus given by

$$P = \left[1 - \prod_{i=1}^{H}(1-\rho_i^F)\right]^w \tag{1}$$

where w is the number of wavelengths per fiber, F is the number of fibers in each hop $\rho_i = \frac{\lambda_i}{\mu_i}$ is the probability that a wavelength is used on a hop, λ_i is the arrival rate per wavelength, and μ_i is the service rate per wavelength. ρ_i is also a measure of the load per wavelength.

We compare multi-fiber case with a single fiber network with the same number of wavelengths ($W = F \cdot w$). Thus for the single fiber network, the blocking probability along the path is

$$P = \left[1 - \prod_{i=1}^{H}(1-\rho_i)\right]^W \tag{2}$$

The end-to-end throughput, given a blocking probability of P with respect to a certain source-destination load G in a network is given by

$$S = (1 - P) \cdot G \tag{3}$$

The change in the blocking probability P due to the load of the connection under consideration, G, is neglected. This is due to the fact that the total capacity of the link used in optical fiber is typically significantly higher than the load generated by a single source-destination pair.

The throughput gain in the case of the multi-fiber multi-hop network without the conversion option, with respect to the single fiber situation, increases appreciably due to lower blocking probability and higher throughput. This gain is a significant improvement that reflects on the end-to-end path blocking probability and the overall network performance, when the total number of wavelengths is equal in both cases:

$$Gain = \frac{1 - \left[1 - \prod_{i=1}^{H}(1-\rho_i^F)\right]^w}{1 - \left[1 - \prod_{i=1}^{H}(1-\rho_i)\right]^W} \tag{4}$$

where *w* is the number of wavelengths available on each fiber in multi-fiber case and *W* is the total number of wavelengths available in a hop in the single fiber case. The gain in the achievable throughput comes at the cost of adding multiple fibers between nodes with similar sets of wavelengths in each fiber. It increases as the blocking probability of a given path decreases. The performance improvement aspects and the effects of different parameters are presented in section 6.

IV. BLOCKING PROBABILITY FOR PATHS WITH WAVELENGTH CONVERSION

In this section we model the performance of networks with different wavelength conversion schemes as well as the different wavelength conversion sharing mechanisms. *C* denotes the number of wavelength converters in the wavelength converter banks. The total number of wavelengths available on all fibers in a hop is *W*, $W = w \cdot F$, and $C = W \cdot DC$, where *DC* is a fraction that represents the number of converters with respect to *W*. The probability that zero converters are busy P_{0_i} and the probability of all converters are busy P_{C_i} for the single-fiber case are derived from *M/M/C/C* model as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{C} (\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho_i^{2 \cdot k}} \qquad (5)$$

$$P_{C_i} = \frac{1}{C!} \cdot \frac{W!}{(W-C)!} \cdot \rho_i^{2 \cdot C} \cdot P_{0_i} \qquad (6)$$

Since in such a model, a conversion request is either accepted or rejected in its entirety, P_{C_i} is proportional to the number of converters *C*, the number of incoming wavelengths, and the load per wavelength ρ_i.

Considering the case of a single-fiber with partial conversion, no blocking occurs when the original requested wavelength is available in each hop, or in case it is not available and at least one wavelength converter in the conversion bank is free and at least one other wavelength is free. The availability of a wavelength along the path that traverses *H* hops is shown in figure 6 and given by:

$$A = \prod_{i=1}^{H} \left[(1 - \rho_i) + \rho_i \cdot (1 - P_{C_i}) \cdot (1 - \rho_i^{W-1})\right] \qquad (7)$$

In this case the blocking probability is given by:

$$\begin{aligned} P \;&=\; 1 - \prod_{i=1}^{H} \Big[(1 - \rho_i) \\ &+\; \rho_i \cdot (1 - P_{C_i}) \cdot (1 - \rho_i^{W-1})\Big] \end{aligned} \qquad (8)$$

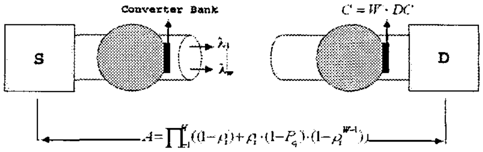

Fig. 6. End-to-end availability for a single fiber hop with conversion

In the case of share-per-link WCS, the CRAA considered switches the incoming wavelength to the desired outgoing wavelength as follows: if the original requested wavelength is not available in any outgoing fiber, the request will be forwarded to the conversion bank that belongs to the same fiber. If there is no free wavelength available on the outgoing fiber or there is no free converter in the conversion bank that belongs to it, then the request is blocked.

A limited number of channel converter allows a limited number of optical paths to share wavelength converters. P_{0_i} and P_{C_i} for the multi-fiber multi-hop case with limited wavelength conversion employing share-per link WCS are derived as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{c} (\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{k \cdot F + k}} \qquad (9)$$

$$P_{C_i} = \frac{1}{c!} \cdot \frac{w!}{(w-c)!} \cdot \rho_i^{c \cdot F + c} \cdot P_{0_i} \qquad (10)$$

The avilability, *A*, along the path is shown in figure 7. The lower case c denotes the number of converters with respect to the total number of wavelengths available on each fiber *w*, where $w = \frac{W}{F}$ and $c = (w \cdot DC)$. Expression 11 shows the blocking probability for the multi-fiber multi-hop case with limited wavelength conversion employing share-per link WCS.

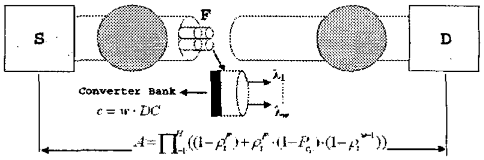

Fig. 7. End-to-end availability for multi-fiber hop with share-per-link conversion

$$\begin{aligned} P \;&=\; 1 - \prod_{i=1}^{H} \Big[(1 - \rho_i^F) \\ &+\; \rho_i^F \cdot (1 - P_{C_i}) \cdot (1 - \rho_i^{w-1})\Big] \end{aligned} \qquad (11)$$

In the model for share-per-node conversion bank, the request rate for a converter is the arrival rate per wavelength λ given that the same wavelength is busy in all output fibers (an event with probability of ρ_i^F). So, a conversion request rate due to a single wavelength is obtained by $(\rho_i^F \cdot \lambda_i)$. Consequently, the transient rate from state *i (i converters are busy)* to state *i+1* is $((W-1)\cdot\rho_i^F\cdot\lambda)$. The probability that zero converters are busy P_0 and the probability that all converters are busy P_C are derived from *M/M/C/C* model shown in figure 8 to predict the behavior of the conversion bank.

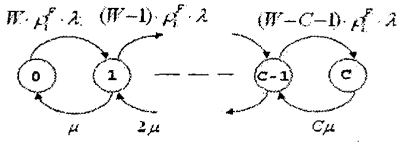

Fig. 8. *M/M/C/C* model for share-per-node conversion bank

$$P_{0_i} = \frac{1}{1+\sum_{k=1}^{C}(\frac{1}{k!})\cdot(\frac{W!}{(W-k)!})\cdot\rho_i^{k\cdot F+k}} \tag{12}$$

$$P_{C_i} = \frac{1}{C!}\cdot\frac{W!}{(W-C)!}\cdot\rho_i^{C\cdot F+C}\cdot P_{0_i} \tag{13}$$

The avilability of a wavelength , A, along the path in the case of multi-fiber hop with share-per-node conversion is shown in figure 9.

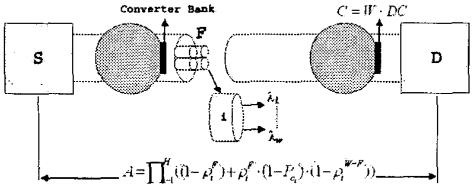

Fig. 9. End-to-end availability for multi-fiber multi-hop with share-per-node

The blocking probability obtained for the limited wavelength conversion case employing share-per-node WCS is thus given by.

$$\begin{aligned} P &= 1-\prod_{i=1}^{H}\Big[(1-\rho_i^F) \\ &\quad + \rho_i^F\cdot(1-P_{C_i})\cdot(1-\rho_i^{W-F})\Big] \end{aligned} \tag{14}$$

The above equation shows an improvement in performance compared to the blocking probability obtained by using share-per-link WCS when the total number of converters are the same in both cases. This result will be demonstrated and explained further in the result section.

When full-range wavelength conversion is considered by employing dedicated WCS, the blocking probability, shown in expression 15, for the multi-fiber multi-hop converges with the blocking probability of the single fiber full conversion case.

$$P = 1-\prod_{i=1}^{H}(1-\rho_i^W) \tag{15}$$

It is notable that for a fully loaded network and a given number of wavelengths, full conversion does not improve performance significantly. This fact will also be demonstrated in the result section.

The achievable throughput gain obtained in this case comes at the cost of adding wavelength conversion. The throughput gain in the case of the dedicated WCS (multi-fiber with full conversion option) with respect to the multi-fiber with no conversion option increases appreciably due to the improvement in blocking performance. This gain improves the end-to-end path blocking probability and the overall network performance significantly as shown in equation 16.

$$Gain = \frac{1-\left[1-\prod_{i=1}^{H}(1-\rho_i^W)\right]}{1-\left[1-\prod_{i=1}^{H}(1-\rho_i^F)\right]^w} \tag{16}$$

V. RESULTS FOR PATHS WITHOUT WAVELENGTH CONVERSION

In this section, we discuss the performance improvements in the multi-fiber environment over the single-fiber multi-hop case considering all network parameters in the absence of wavelength conversion. In figure 10, the source-destination throughput (expression 4) with respect to G, which is significantly less than the capacity of the link, is plotted as a function of the number of wavelengths in the multi-fiber case for different path lengths (intermediate hops) for $\rho_i = 0.7$. It shows that utilization decreases when the number of hops, H, increases and the number of wavelengths in the fiber, w, decreases. Throughput always increases along with the number of wavelengths, which can provide additional network capacity to handle the traffic. The throughput improvement due to the use of multi-fiber in a network with a diameter of 5-hops is considerable with respect to the performance of the single-fiber no conversion case. In the multi-fiber case, we have more freedom with the network diameter as apposed to the single fiber case

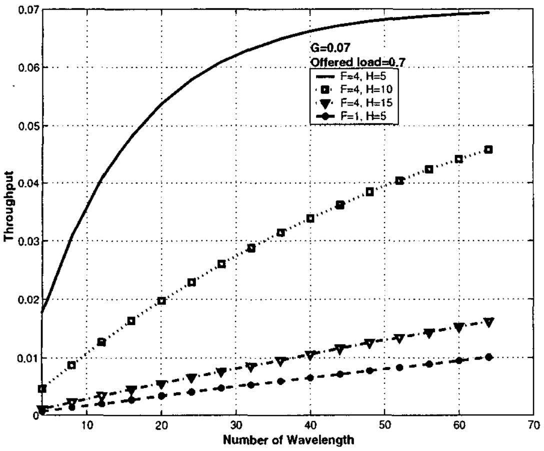

Fig. 10. Throughput vs. number of wavelength

due to the improvement in the throughput resulting from the ability to accommodate multiple requests for the same wavelength in different fibers in the same hop. Using multiple fibers compensate for the throughput degradation caused by the number of hops that a path traverses. The figure shows a considerable improvement in throughput for similar network parameters, where the number of wavelengths is divided among multiple fibers used in links between nodes.

In figure 11, blocking probability is plotted as a function of offered load for the multi-fiber case with 4 fibers and 4 wavelengths per fiber for different path lengths (intermediate hops). It offers almost zero blocking until

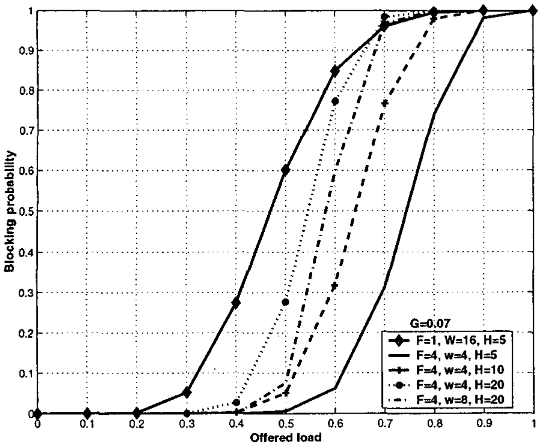

Fig. 11. Blocking probability vs. offered load

the offered load reaches approximately 40%in all multi-fiber hop cases studied. An example of a 5-hop network diameter shows a dramatic improvement of blocking performance in the multi-fiber case compared to the single-fiber case. It should be noted that the increase of the number of wavelengths in the fiber will further improve the optical path blocking probability, which in turn improves the throughput performance of the network and increases the possible reach of the network by increasing the deployable network diameter. The results for 8, 16, and 32 wavelengths per fiber were generated and verified.

Figure 12 demonstrates the imperative role of network diameter on determining throughput. The figure shows that even though network diameter has doubled, the multi-fiber case improves the throughput for the same values of network parameters.

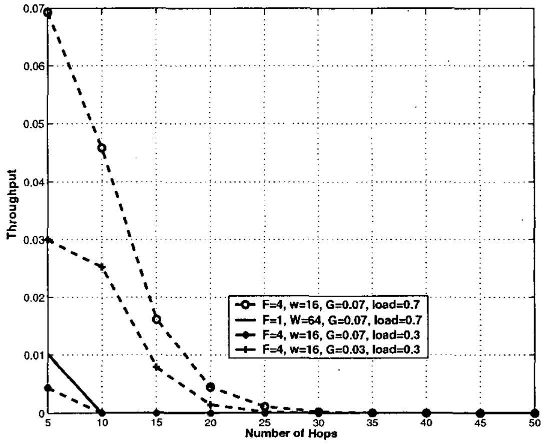

Fig. 12. Throughput vs. number of hops

In figure 13, throughput is plotted as a function of number of wavelengths in the multi-fiber case for the same path length. The graph confirms that the increase of the number of fibers in the intermediate hops will improves the throughput performance of the network. It also shows that throughput increases with the number of fibers in each link and the number of wavelengths carried in each fiber.

In figure 14, throughput is plotted as a function of offered load in the multi-fiber multi-hop case for different networks with different parameters. Using a network with parameters w=4, H=20, and F=4 as a reference, we notice that the increase of the number of wavelengths w will increases the throughput. It is also noticed that the decrease of the number of hops, H, that a path traverses increases the throughput significantly at the cost of network diameter and network reach, which is not practical for the ever growing optical domain. The network with parameters $w=4$, $H=20$, and $F=8$

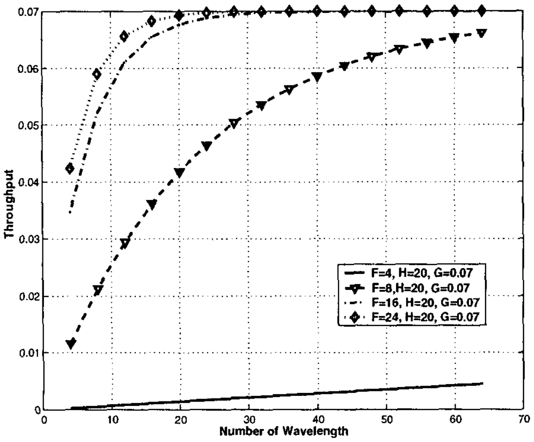

Fig. 13. Throughput vs. number of wavelengths in multi-fiber multi-multi-hop case

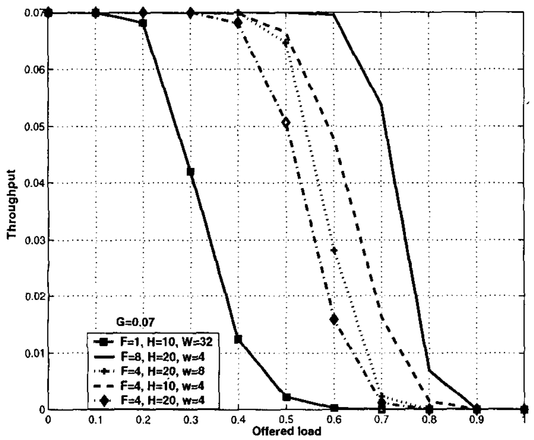

Fig. 14. Throughput vs. offered load for different networks

confirms the main objective of this study. It shows that the increase of the number of fibers, *F*, in links deployed between nodes have the dominating effect in improving the throughput performance, reducing the path blocking probability, and increasing the network reach by increasing the diameter. The figure also shows that the increase of offered load reinforces the negative effect of network diameter on the throughput performance and consequently the end-to-end blocking probability.

As a measure of the benefit of multi-fiber multi-hop environment, the gain was defined as the increase in achievable throughput with respect to the single fiber case. Figure 15 shows that the multi-fiber system offers better performance in large networks due to significantly higher gain with reference to single fiber system given that other network parameters are fixed. It also shows a tremendous gain, that comes at the cost of adding more fibers between nodes, when the offered load increases. It is economically more feasible to use single-fiber link where the expected offered load is low due to the fact that the increase in the number of fibers would not increase the throughput performance. This means that the blocking probability would be a comparable quantitatively when the expected offered load is low.

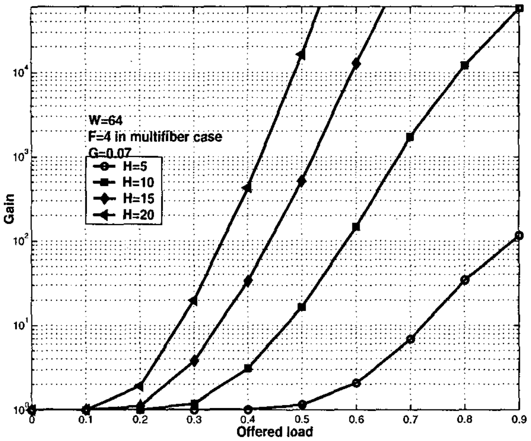

Fig. 15. Gain vs. offered load

VI. RESULTS FOR PATHS WITH WAVELENGTH CONVERSION OPTION

In this section, we discuss results showing the performance improvements in the multi-fiber environment with various wavelength conversion options considering all network parameters. In figure 16, the throughput is plotted as a function of the number of wavelengths in the multi-fiber case with 50% conversion for different WCS architectures and a single path network of 20 hops. The throughput improvement due to the use of wavelength conversion depends on the degree of conversion. The use of wavelength conversion increases the degree of freedom to increase network diameter due to the improvement in throughput resulting from the ability to minimize wavelength contention. It is noted that a degree of 70% conversion resulted in performance that is very comparable quantitatively to full-range conversion in the share-per node WCS case. This indicates that the increase of conversion range at higher wavelength count does not result in a significantly higher performance. It also shows that smaller degree of conversion can yield the same performance as full-range wavelength conversion due to low network throughput where some wavelength converters remain unused.

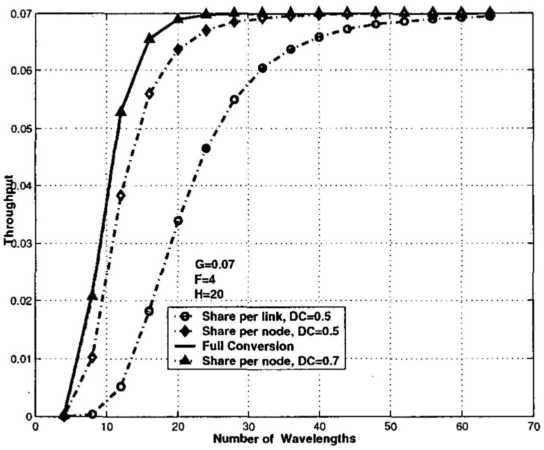

Fig. 16. Throughput vs. number of wavelength

In Figure 17, the blocking probability is plotted as a function of offered load for different WCS architectures. In the case of shared converter architectures, it verifies that the efficiency of wavelength converters increases with the blocking performance and utilization of the system. It should be noted that at lower rates of offered load, the blocking performance of all cases considered are comparable. The region of comparable blocking performance increases with the increase of degree of conversion. This introduces the issue of cost effectiveness when considering different switching architectures, conversion options, and hop configurations. It is observed that the effects of conversion are mainly reliant on path length and traffic pattern on the link.

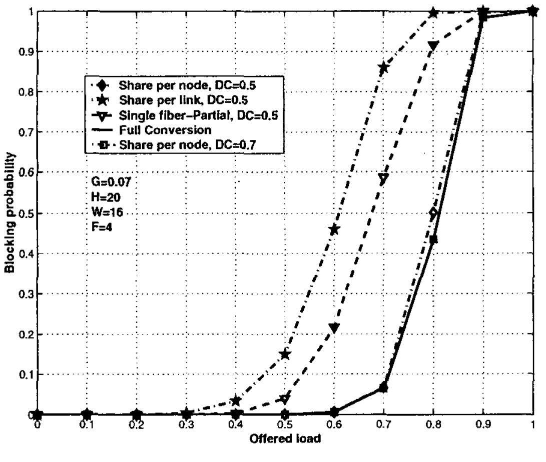

Fig. 17. Blocking probability vs. offered load

As a measure of the benefit of wavelength conversion in multi-fiber multi-hop environment, the gain was defined as the increase in achievable throughput with respect to the full-range conversion case. Figure 18 shows better gain performance at higher rates of offered load when using switches that employs wavelength converter with sharing mechanism. It is more economically feasible to use WCSs with conversion sharing and lower hardware complexity to reduce wavelength blocking probabilities and obtain better throughput gain. Results also prove that share-per-node is the most efficient and its performance reaches that of full-range conversion at 70% wavelength conversion. This means that the blocking probability would be comparable quantitatively to full-range conversion due to the optimized use of conversion resources. Using different CRAAs, which dynamically accommodate more conversion requests, for share-per-link WCS improves its performance. It also shows that the gain increases as the number of converters increases and saturates as the number of converters is greater than some threshold and less than the total number of channels on the link, which implies that a limited range of conversion under certain offered loads is sufficient to provide good performance.

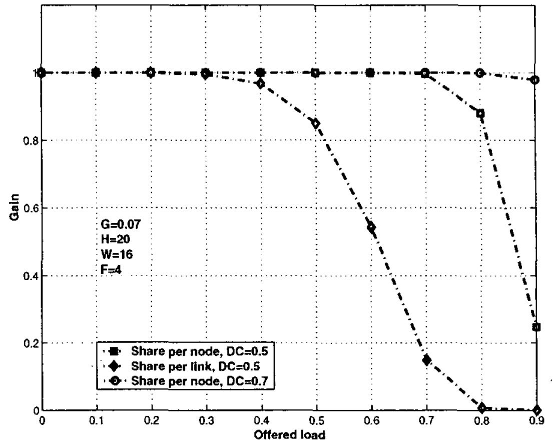

Fig. 18. Gain vs. offered load

In figure 19, The end-to-end throughput for a source-destination pair is plotted as a function of conversion percentage(DC). As expected, the throughput increases as the number of converters increases. However, after an initial steep increase, the curves generally tend to flatten as the number of converters increases. This behavior is consistent with the results of earlier observations.

VII. Conclusion

In this paper, the trade-offs involving the use of multi-fiber multi-hop networks such as the number of fibers,

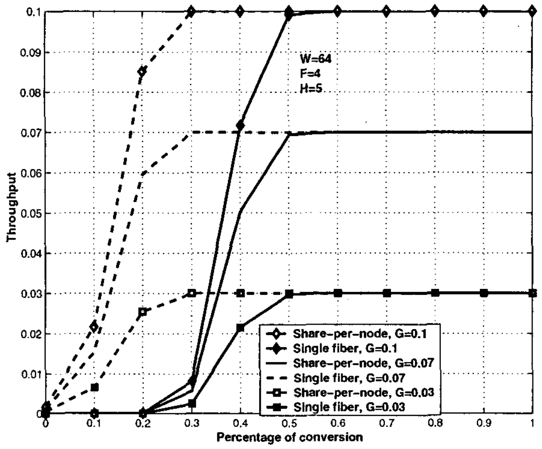

Fig. 19. Throughput vs. Percentage of conversion

number of wavelengths, conversion options, and the different switch configurations were studied in terms of key performance metrics such as end-to-end blocking and throughput.

The study shows that the use of multiple fibers in multi-hop networks reduces the end-to-end blocking probability by reusing the same set of wavelengths in multiple fibers and by increasing the availability of the end-to-end paths. The use of multiple fibers compensate for the throughput degradation caused by the increase in the hop count that a path traverses. It also adds more flexibility in increasing network reach (diameter) without effecting throughput significantly. It helps reduce the cross-talk problem resulting from having a large number of channels in a single fiber using DWDM fine spacing techniques; it helps to overcome the capacity exhaustion problem in C-band window by offering the same set of wavelengths on multiple fibers.

The use of wavelength conversion increases the improvement in throughput resulting from the ability to minimize wavelength contention. Wavelength conversion may possibly improve the performance of the network by resolving the wavelength contention problem, but it incurs increased cost, hardware complexity, and space requirements implying potential trade-offs between the performance and the number of wavelength converters needed. The cost of using wavelength conversion could be adjusted by employing conversion resources sharing schemes. Results show that share-per-node WCS is the most efficient. It provides a sufficient and decent performance compared to full wavelength case. Considering more intelligent CRAAs that dynamically accommodate more conversion request for share-per-link WCS will improve the overall performance at the expense of control algorithm complexity.

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