Path Blocking Performance in Multi-Fiber Wavelength Routing Networks with and without Wavelength Conversion

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Abstract— **The tradeoffs involving the use of multi-fiber multi-hop networks such as the number of fibers, number of wavelengths, conversion options, and the different switch configurations are examined, and their impact on end-to-end blocking and throughput performance is evaluated. Models relating network parameters to end-to-end performance of circuit switched all-optical networks are developed. The performance gain due to the use of multiple fibers with or without conversion proved to be superior to the single fiber case, when the total number of wavelength are the same, for traffic that traverses multiple hops between source and destination nodes.**

I. INTRODUCTION

Wavelength routing is used to establish end-to-end all-optical lightpaths to route optical signals between pairs of source-destination nodes in circuit switched dense wavelength division multiplexing (DWDM) networks. Wavelength routing provides transparent data communication channels that overcome electronic processing bottlenecks at intermediate nodes.

In the absence of wavelength conversion, [4], the same wavelength has to be employed for a connection on every hop along an optical path. A connection request is blocked when the wavelength is not found in any intermediate hop between the source-destination pair, even if different wavelengths are free in that hop, causing higher network contention and blocking probability according to the wavelength continuity constraint [13]. Performance wise, it is advantageous to permit incoming wavelengths in intermediate nodes to be converted to different outgoing wavelengths.

Blocking probability in wavelength-routed optical networks has been studied previously [4], [10], [15]. This paper, By contrast, considers the performance issues for the multi-fiber multi-hop case with and without wavelength conversion capabilities. Currently, WDM systems are being deployed using the wavelength region ranging from 1530 to 1560 nm, denoted as the C-Band. The rapid growth of traffic will push the need for an even greater transmission capacity. Trying to add more channels into a single fiber using DWDM fine spacing techniques reduces the wavelength stability by increasing channel cross-talk. A fiber cable consists of multiple strands. Therefore, an alternative approach for increasing the number of channels is to light multiple fibers, each using the same set of wavelengths. This, in addition to overcoming the capacity exhaustion problem in C-Band window, provides significant performance advantages as well. Performance advantages are a result of the architectural flexibility that allows a wavelength to be routed into any of the parallel fibers. Wavelength conversion, if available, provides another mechanism for enhancing the end-to-end performance.

We compare networks where every node is connected to its neighbors with one fiber as in [2] to networks that employ multiple fibers between nodes. The improvements of key performance metrics such as end-to-end blocking performance and throughput, in wavelength routing networks employing multi-fiber multi-hop architecture under different wavelength conversion scenarios, are investigated. Closed-form expressions are derived to show the improvement in throughput under various operational scenarios.

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

II. MULTI-HOP CONFIGURATIONS

The model for a single-fiber multi-hop environment without wavelength converters in [1] approximates the blocking probability along a path for a multi-hop single fiber between nodes with uniformly distributed load on all links entering the intermediate nodes by

$$P = (1 - (1 - \rho)^H)^W \tag{1}$$

where H denotes the number of hops along a path, W the total number of wavelengths in the hop, $\rho = \frac{\lambda}{\mu}$ is the probability that a wavelength is used in a hop, λ is the arrival rate per wavelength, and μ is the service rate per wavelength. ρ is also a measure of the load per wavelength. The blocking probability P is the probability that no wavelength is available to setup a connection between the source and the destination, i.e. each wavelength is used on at least one of the intermediate hops H. The work in [1] considers a system with a single fiber where the edge node receives a request for a specific wavelength from

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the source. In all systems considered in this paper, the edge node receives a connection request from the source without specifying the outgoing wavelength. Accordingly, a request can use any wavelength at the edge node, where it is permitted to choose one of the *W* wavelengths available in the hop.

III. WAVELENGTH CONVERSION OPTIONS

Wavelength convertible switches (WCS), optical switches (OSW) employing wavelength converters (WC) [4], offer flexible lightpath switching, contention resolution, network interoperability as well as transparency of the optical layer [8]. 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 [11], [14]. Two major categories of WCS are reviewed next.

The *dedicated WCS* offers a wavelength converter for each outgoing wavelength allowing any incoming wavelength to be switched at desired wavelength to the desired link [7]. The dedicated WCS is the least cost efficient, but most flexible, architecture.

More cost effective architectures use different converter sharing mechanisms [5], [9]. *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 1 [7]. For increased performance efficiency and reduced hardware cost, wavelength routing protocols are responsible for better conservation of conversion resources where converters are not dedicated to individual channels or to any specific out going link.

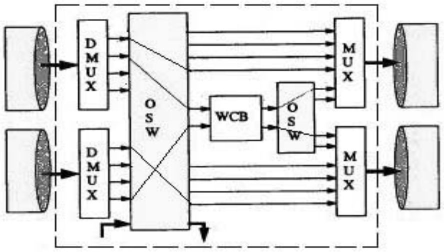

Fig. 1. Share-per-node wavelength-convertible switch[7]

IV. BLOCKING PROBABILITY FOR PATHS WITHOUT WAVELENGTH CONVERSION

Considering the configuration shown in figure 2, we assume the same number of fibers in all hops in the path between the source-destination pair of interest (S, D). The blocking probability *P* is the probability that each wavelength in every fiber is used on at least one of the *H* intermediate hops. *P* is thus given by

$$P = (1 - (1 - \rho^F)^H)^w \tag{2}$$

where *F* is the number of fibers and *w* is the number of wavelengths per fiber. The total number of channels in a hop is *W*, where $W = w \cdot F$.

The achievable end-to-end throughput for a given blocking probability with respect to a certain source-destination load *G* in the network, with or without wavelength conversion, is given by:

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

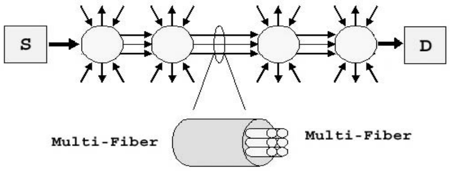

Fig. 2. A multi-hop request in a multi-fiber multi-hop environment

The change in the blocking probability *P* due to the load of the connection under consideration, *G*, is neglected, i.e. ρ is assumed to be a given constant value,not affected by G. This is due to the fact that the total capacity of the link, the optical fibers, is typically significantly higher than the load generated by a single source-destination pair.

V. BLOCKING PROBABILITY FOR PATHS WITH WAVELENGTH CONVERSION

Consider the architecture shown in figure 2 where each node has a set of converters shared as in 1. We assume that requests for a given wavelength follow a Poisson arrival process with rate λ and that the service time is exponential with a mean rate μ. The probability that no converter is busy, P_0, and the probability that all the converters are busy, P_C, are derived from *M/M/C/C* model shown in figure 3 to predict the behavior of the conversion bank. *C* denotes the number of wavelength converters in the wavelength converter bank in each switch. Let $C = W \cdot D_C$, where D_C is a fraction that represents the number of converters with respect to W.

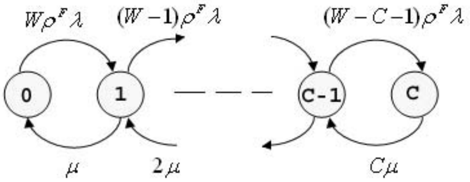

Fig. 3. *M/M/C/C* model for share-per-node conversion bank

In the model for share-per-node conversion bank case, the request 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 ρ^F. So, a converter request rate due to a single wavelength is $\rho^F \cdot \lambda$. Consequently, the transient rate from state *i (i converters are busy)* to state *i+1 (i+1 converters are busy)* can be approximated by $(W - i) \cdot \rho^F \cdot \lambda$. P_0 and P_C for share-per-node WCS can thus be derived as follows:

$$P_0 = \frac{1}{1 + \sum_{k=1}^{C} (\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho^{k \cdot F + k}} \tag{4}$$

$$P_C = \frac{1}{C!} \cdot \frac{W!}{(W-C)!} \cdot \rho^{C \cdot F + C} \cdot P_0 \quad (5)$$

P_C depends on the number of converters C, number of incoming wavelengths, W, and the load per wavelength ρ.

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

$$P = (1 - ((1 - \rho^F) + \rho^F \cdot (1 - P_C) \cdot (1 - \rho^{W-F}))^H)^w \quad (6)$$

Results for single-fiber partial conversion case can be obtained by substituting F*=1*. Figure 1 shows the architecture of share-per-node WCS. Expression 6 indicates an improvement in performance with multiple fibers ($F > 1$) compared to that using single-fiber ($F = 1$) when the number of total converters and the total number of wavelengths are the same in both cases.

When full-range wavelength conversion is considered by employing dedicated WCS, the blocking probability can be obtained by setting $P_C = 0$ in equation 6:

$$P = (1 - (1 - \rho^W)^H)^w \quad (7)$$

The blocking probability for the single-fiber full conversion case equals to that of multi-fiber full conversion case. Similarly, $P_C = 1$ corresponds to the case where there are no wavelength converts.

The performance gain is calculated as the ratio between the blocking probabilities for multi-fiber partial conversion case, which is considered as the general form, and the dedicated WCS (multi-fiber full conversion option) case.

$$g = \frac{1 - (1 - ((1 - \rho^F) + \rho^F \cdot (1 - P_C) \cdot (1 - \rho^{W-F}))^H)^w}{1 - (1 - (1 - \rho^W)^H)^w} \quad (8)$$

Table I summarizes all the different scenarios for the different switches considered in this paper according to their blocking probabilities.

Switch	Blocking Probability P
Multi-fiber Partial Conversion (share-per node WCS)	$(1 - ((1 - \rho^F) + \rho^F \cdot (1 - P_C) \cdot (1 - \rho^{W-F}))^H)^w$
Single-fiber partial conversion	$(1 - ((1 - \rho) + \rho \cdot (1 - P_C) \cdot (1 - \rho^{W-1}))^H)^w$
Full Conversion (Dedicate WCS)	$(1 - (1 - \rho^W)^H)^w$
Multi-fiber no conversion	$(1 - (1 - \rho^F)^H)^w$
Single-fiber no conversion	$(1 - (1 - \rho)^H)^W$

TABLE I

SWITCH BLOCKING PROBABILITY

VI. RESULTS

In this section, we discuss the performance improvements in the multi-fiber environment over the single-fiber case considering all network parameters. The throughput is related to the blocking probabilty as in expression 3. In figure 4, the source-destination throughput is plotted as a function of the total number of wavelengths, W, for different path lengths (intermediate hops, H=5,15) for $\rho = 0.7$ and G*=0.07*. $F = 1$ corresponds to single-fiber, and $F = 4$ to four parallel fibers. It shows that throughput decreases with the number of hops H and increases with the total number of wavelengths, W in the fiber. 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 5-hop diameter is considerable with respect to the performance of the single-fiber no conversion case as shown in the figure 4. In the multi-fiber case, we have more freedom with network diameter due to the improvement in the throughput resulting from the ability to accommodate multiple requests for the same wavelength. Using multiple fibers compensates for the throughput degradation caused by the number of hops that a path traverses.

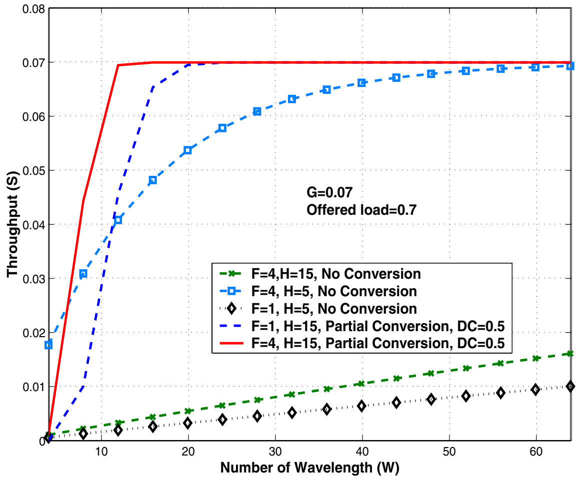

Fig. 4. Throughput vs. number of wavelength

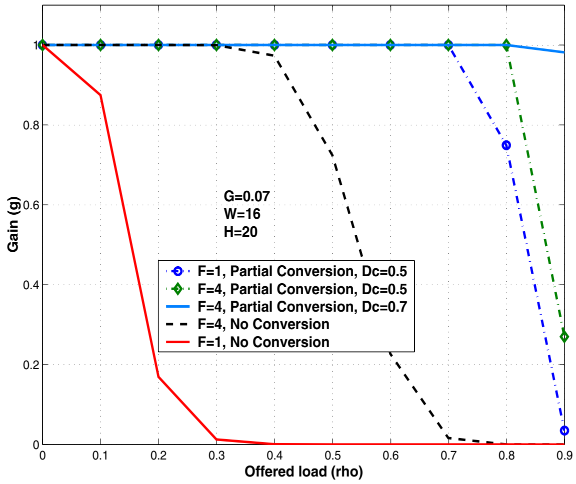

Fig. 5. Gain vs. offered load

As a measure of the benefit of wavelength conversion in multi-fiber multi-hop environment, the gain was obtained for single-fiber partial conversion, multi-fiber no conversion, and multi-fiber employing share-per-node WCS with respect to the full-range conversion case using equation 8. Figure 5 shows better gain in performance at higher rates of offered load when using switches that employ wavelength converter with sharing mechanism. Results also prove that performance of share-per-node 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. 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 load is sufficient to provide decent performance.

In figure 6, the end-to-end throughput for a source-destination pair is plotted as a function of conversion rate. 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. It also can be seen that the performance enhancement achieved by having multiple fibers can be achieved in single-fiber networks by having a higher number of wavelength converters.

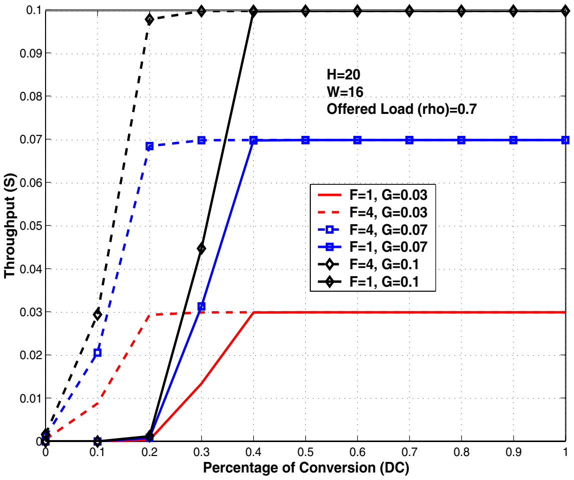

Fig. 6. Throughput vs. percentage of conversion

VII. CONCLUSION

In this paper, the end-to-end performance of circuit switched all-optical networks in multi-fiber multi-hop environments is modeled and evaluated with and without wavelength conversion. The study shows that the use of multiple fibers in each hop provides an additional network capacity and increases network throughput by reusing the same set of wavelengths in multiple fibers. Thus, the multi-fiber configuration helps achieve a higher and efficient throughput in the wavelength routing optical networks. Alternatively the use of multiple fibers can compensate for the throughput degradation caused by the increase in the hop count that a path traverses. It helps reduce the cross-talk problem resulting from adding more channels into a single fiber using DWDM fine spacing techniques, and also helps to overcome the capacity exhaustion problem in C-Band window by using the same set of wavelengths on multiple fibers.

Wavelength conversion is studied for its performance improvement in terms of blocking probability and throughput. The use of wavelength conversion increases the throughput resulting from reduced wavelength contention. As the number of fibers per link increases, the advantages of having wavelength converters and the performance gained accordingly decreases. 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.

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