On Trading Wavelengths With Fibers: A Cost-Performance Based Study

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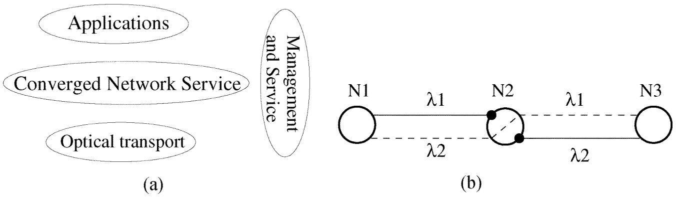
***Abstract*—We consider the effect of multiple fibers on wavelength division multiplexing networks without wavelength conversion. We study networks with dynamic wavelength routing and develop accurate analytical models to compare various possible options using single- and multiple-fiber networks. We use results of an analytical model and simulation-based studies to evaluate the blocking performance and cost of multifiber networks. The number of fibers required providing high performance in multifiber networks and their costs are compared. A case is made for using multiple fibers in each link with fewer wavelengths instead of using a single fiber with many wavelengths. In particular, we show that a network with four fibers per link and with four wavelengths on each fiber without any wavelength conversion on any node yields similar same performance as the networks with one fiber per link and 16 wavelengths per fiber on each link and with full wavelength conversion capability on all nodes. In addition, the multifiber network may also offer the cost advantage depending on the relative cost of components. We develop a parametric cost model to show that multiple fibers in each link are an attractive option. Finally, such multifiber networks also has fault tolerance, with respect to a single fiber failure, already built into the system.**

***Index Terms*—Analytical/parametric cost model, cost-performance analysis, multifiber WDM networks, optical networking, optical system cost model.**

I. INTRODUCTION

COMPUTER and telecommunication networks are changing the world dramatically. The Internet, mainly based on packet switches, provides very flexible data services such as e-mail and access to the World Wide Web. The Internet is a variable-delay, variable-bandwidth network that provides no guarantee on the quality of service (QoS) in its initial phase. The Internet traffic volume continues to grow exponentially. A conservative estimate of Internet traffic growth is that it is doubling every six months [1]. Various efforts are being made to provide high levels of QoS on packet networks—particularly for voice and other real-time services.

On the other hand, over the past two decades, optical fibers have revolutionized the communications industry. A natural approach to utilize the fiber bandwidth efficiently is to partition the usable bandwidth into nonoverlapping wavelength bands. Each wavelength, operating at several gigabits per second, is used at the electronic speed of the end-users. This mechanism is called wavelength division multiplexing (WDM) [3], and is the most promising candidate for improving fiber bandwidth utilization in future optical networks. The research, development, and deployment of WDM and dense WDM (DWDM) technologies are now evolving at a rapid pace to fulfill the increasing bandwidth requirement and deploy new network services. In particular, with the new development of the low-loss optical fiber, the true terahertz bandwidth capability of the fiber can be harnessed. This is due to the fact that the new Lucent AllWave fiber expands the range of usable wavelengths from 1280 to 1625 nm, allowing a 50% increase in the available bandwidth. In addition, with the new development of optical switches, the feasibility of an all optical network does not seem too far away [16].



(a) (b)

Fig. 1. (a) Next-generation network architecture. (b) Demonstration of wavelength continuity constraint on a two-hop path in a network.

With increasing data traffic and high levels of QoS requirement on packet networks, it is desirable to converge the multiple networks around a single packet-based core network [2]. The *next-generation Internet* (NGI) architecture will converge to share a common high-level architecture as shown in Fig. 1(a).

The application signals have widely varied characteristics such as signal format and transmission speed. To transport the varied application signals on the optical transport network, a network service layer is needed to map the signals to optical channel signals along with associated protocols to assure proper networking functions. This layer captures today's IP and ATM capabilities with statistical multiplexing and QoS guarantee.

The network service layer relies entirely on the transport layer for the delivery of multigigabit bandwidth where and when it is needed to connect to their peers. The optical transport layer is capable of delivering multigigabit bandwidth with high reliability. It has advanced features such as optical channel routing and switching and supports flexible, scalable, and reliable transport of a wide variety of client signals at ultra-high speed. Transport networking enables the service layer to operate more effectively, freeing them from physical topology constraints to focus on the sufficiently large challenge of meeting service requirements.

Manuscript received March 28, 2002; revised June 17, 2003; approved by IEEE/ACM TRANSACTIONS ON NETWORKING Editor R. Srikant. This work was supported in part by the National Science Foundation under Grant ANI9973102 and in part by the Defense Advanced Research Projects Agency under Prime Award N66001-00-1-8949, Project ANI2666, subcontract 00-S04.

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Digital Object Identifier 10.1109/TNET.2004.836130

This paper briefly reviews some general trends in the practical development of optical network systems. Then wavelength routed networks as well as networks with wavelength conversion capabilities are reviewed. Next, we discuss the concept of multifiber networks. Using the results of an analytical study and simulation experiments, we establish that multifibers per link in a network can minimize the need of wavelength conversion. Next, we develop a parametric model for cost estimation for the networks that deploy multifibers on each linkand/or full wavelength conversion at all nodes. Using the results of this model, we show the premise of trading wavelengths with fibers as a practical consideration.

II. TRENDS IN OPTICAL NETWORKS DEPLOYMENTS

The promise of broadband communication capability in gigahertz and terahertz has been a great driving force for accelerated development of WDM and DWDM networks. In the 1980's, Deutsche Telecom introduced the technology that was a 10-channel system (with 36-nm channel spacing and 20-nm signal pass bandwidths). During the second half of the last decade some noteworthy implementations were commercialized and multiple units were sold internationally, such as Pirelli's 4-wavelength, AT&T's 8-wavelength, and IBM's 20-wavelength (IBM's 9729) systems. In order to achieve more bandwidth out of the existing fibers few DWDM systems were proposed as commercial possibility in 1998–1999. Eventually in 1999, Lucent Technologies won the first order for an 80-channel system, and Pirelli offered a system that was scalable up to 128 channels. In all of the cases, the contracts were for systems that were upgradable in the future.

While technologically feasible, such complete systems with full functionality can be a huge financial burden on the customer. Consequently, companies implement systems that are affordable and offer real possibility of future expansion. Due to cost factors in 1999–2000, only four to eight (and in some cases 16) wavelengths of the 80 to 128 channels were being utilized. During the same period, some companies were contracting to provide custom-made solutions up to 32 channels [4], [5]. Meanwhile, few companies with established SONET product lines announced platforms that were scalable up to 32 wavelengths (i.e., Alidian's OSN 4800 and Alcatel's Optinex 1686WM). Finally, in the years 2000–2002 more wavelengths and systems up to 40–64 channels became available in the metro and long-haul applications. Currently, there are few systems that utilizie128 and 160 channels, and the premise of terahertz networks with more than 200 wavelengths for the metro and long-haul systems seems very practical and commercially viable.

The optoelectronic components cost is one of the factors that has hindered the fast penetrating of optical networks in the market. Developers keep searching for new fabrication methods to reduce the prices of switches, transmitters, and receivers. It is difficult to predict when the more economical methods, as well as economy of scale factors, will bring the optical components to a reasonable price level compared to the electronic counter parts.

As a result, solutions that would utilize the available fiber systems, with limited wavelength capabilities seems to offer more realistic and economical alternative for many future expansions. It should be noted that having more fiber (as proposed by this study) will result in constraint reduction. This study shows that utilizing the available infrastructure and reducing the constraints can result in a valid alternative with less cost.

A. Wavelength-Routed WDM Networks

With the advancement of optical technologies, a wide variety of optical components of building WDM networks have been developed, such as wide-band optical amplifiers (OAs), optical add/drop multiplexers (OADMs), and optical cross-connects (OXCs). It becomes possible to route data to their respective destinations based on their wavelengths. The use of wavelength to route data is referred to as wavelength routing, and a network which employs this technique is known as a *wavelength-routed* network [3], [6]. In such networks, each connection between a pair of nodes is assigned a path through the network and a wavelength on that path such that connections whose paths share a common link in the network are assigned different wavelengths. The optical communication path between two nodes is called a *lightpath*. All-optical networks employing wavelength-division multiplexing and wavelength routing are a viable solution for future wide-area networks (WANs) and metropolitan-area networks (MANs). These wavelength-routed WDM networks offer protocol transparency and simplified management and processing compared to routing in telecommunications systems using digital cross-connects [3], [6].

In a wavelength-routed WDM network, the path of a signal is determined by the location of the signal transmitter, the wavelength on which it is transmitted, and the state of the network devices. An example of such a network with two wavelengths on each link is shown in Fig. 1(b). There are two sessions that are in progress, one from node 1 to node 2 using wavelength λ_1, another from node 2 to node 3 using wavelength λ_2. A connection request from node 1 to node 3 has to be blocked, although free wavelengths are available on both link 1 and link 2. This is because of the wavelength continuity constraint, that is, the same wavelength must be assigned to a connection on every link on a path if wavelength converters are not available at the switching nodes. Connection requests encounters higher blocking probability than it does in electronic-switched networks because of the wavelength continuity constraint.

B. Routing and Wavelength Assignment

Routing and wavelength assignment algorithms are responsible for selecting a suitable route and a wavelength among the many possible choices for establishing a connection. Good routing and wavelength assignment algorithms are critically important to improving the performance of WDM networks [19], [20].

The routing algorithms can be broadly classified into two, namely, *static routing* and *dynamic routing*. In static routing, the routes for node pairs are fixed, i.e., the routes do not change with the network status. Static routing typically includes *fixed-path routing (FPR)* and *alternate-path routing (APR)*. In the dynamic routing, the routes for node-pairs are dynamically selected according to the current network status. A typical example of the dynamic routing is least-congestion routing (LCR).

Wavelength assignment problem is a unique problem in WDM networks. Due to wavelength continuity constraint, the same wavelength has to be free on all of the links of a path for establishing a connection in all-optical WDM networks without wavelength conversion. If the full-range wavelength converter is available at every node, wavelength assignment is a trivial problem. However, the technology of all-optical wavelength conversion is not mature yet. Wavelength converters are likely to be costly devices. Therefore, good wavelength assignment algorithms along with routing algorithms are critically important to improving the network performance and reducing the network cost.

Several algorithms have been proposed for wavelength assignment: *random* that chooses one of the available wavelengths randomly with a uniform distribution; *first-fit* that assumes that the wavelengths are arbitrarily ordered, and checks the status of the wavelengths sequentially and chooses the first available wavelength to establish a connection; *most-used* selects a free wavelength that is already being used on the most number of links in the network; and *least-used* that selects the free wavelength that is used on the least number of links in the network. The chosen wavelength is used to establish a connection. The results in [6] show that both of the random and the least-used algorithms distribute the load evenly over the wavelengths. However, the blocking probability of the random and least-used wavelength assignment algorithms is higher than that of the first-fit and most-used algorithms.

III. WAVELENGTH CONVERSION AND ALTERNATES

A WDM network without wavelength conversion is referred as *wavelength selective (WS)* network [7]. The network performance can be improved by using wavelength converters at the switching nodes [8], [20], which can convert data on one wavelength along a link into other wavelengths at an intermediate node and forward it along the next link. The networks with wavelength conversion is called *wavelength interchanging (WI)* networks [7]. The first solution for wavelength conversion is optoelectronic wavelength conversion, in which the optical signal is initially converted into the electronic domain. The electronic signal is then used to drive the input of a tunable laser tuned to the desired output wavelength. Since this technique is not transparent to data bit rate and data format, which is one of the major advantages of using optical networking, the optoelectronic wavelength conversion is not a preferred solution for the future networks. All-optical wavelength converters are being prototyped in research laboratories [8], [17], [18]. Networks with sparse wavelength conversion [9] and limited wavelength conversion [10] have been analyzed in great details. However, the wavelength conversion techniques have not matured yet. Wavelength converters are likely to remain costly devices in the near future.

An alternative solution to conquer the wavelength continuity constraint is to use multifiber WDM networks [11]–[15]. In multifiber networks, each link consists of multiple fibers, and each fiber carries information on multiple wavelengths. A wavelength that cannot continue on the next hop can be switched to another fiber using an OXC if the same wavelength is free on one of the other fibers. Moreover, may also help to support the dramatically increasing bandwidth requirement.

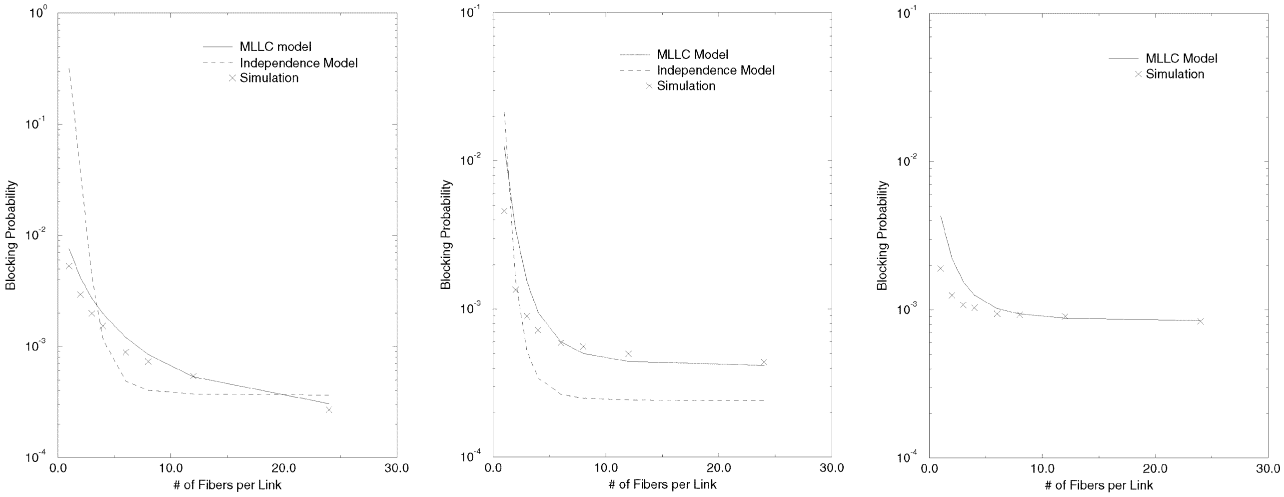
In this paper, we study the blocking performance of multifiber WDM networks with different routing and wavelength assignment algorithms. A parametric system cost model for both multifiber networks and single-fiber wavelength-convertible WDM networks is also developed. By comparing the cost of different network configurations, we show that a multifiber network is a cost-effective solution under current technology. In particular, we show that a network with four fibers per link and with four wavelengths per fiber yields the same performance as the network with one fiber per link with all wavelengths per fiber on each link and full wavelength conversion at all the nodes.

IV. MULTIFIBER WDM NETWORKS

Multifiber WDM networks have been studied in [11]–[15]. Much research has also been done in the literature on WDM networks with limited wavelength conversion [9], [10]. Assuming Poisson input traffic with arrival rate λ at each node, exponentially distributed call holding time with mean $1/\mu$, a single preselected for each source–destination (s–d) pair, a random wavelength assignment, and using analytical and simulation models, it has been shown that a limited number of fibers, each with a fewer wavelength, is sufficient to provide similar performance as that in full-wavelength-convertible networks. Let F denote the number of fibers per link and W denote the number of wavelengths per fiber. We assume that they are the same on all links and fibers, respectively. If the wavelength is not free on all of the F fibers, the request is blocked on this wavelength. No wavelength converter is available at any node.

If we do not account for the cost of wavelength converters, the cost of a multifiber network is likely to be higher than a single-fiber network (more amplifiers and multiplexer/demultiplexer). It should however be noted that a fiber with fewer wavelengths may be able to use cheaper components (like muxes and demuxes) for termination. The design goal of a multifiber network is to achieve high performance with the minimum number of fibers per link. An important problem here is to determine how many fibers are required on each link to guarantee performance that is similar to a network with full-range wavelength converters at every node.

Using a multifiber link-load correlation (MLLC) and link-load independent model, we depict the results of blocking probability for two regular topologies, the ring and the mesh-torus networks, and an irregular NSF T1 backbone network (NSFnet) [6]. The blocking probability on a l-hop path can be computed recursively by viewing the first $l-1$ hops as the first hop and the lth hop as the second hop of a two-hop path [9]. A detailed analysis has been presented in [14], [15]. We are interested in finding the effect of multifibers on these networks. The results we are interested in is that how many fibers, each with fewer wavelength are required to provide similar performance as that in a full-wavelength-convertible network.



(a) (b) (c)

Fig. 2. Blocking probability versus the number of fibers in (a) 10-node unidirectional ring, (b) 5 × 5 mesh-torus, and (c) NSFnet network.

For the results in Fig. 2, the link capacity in all the networks has been fixed at 24 light channels, i.e., $FW = 24$ on each link. We vary the number of fibers on each link, F, to be 1, 2, 3, 4, 6, 8, 12, and 24, and the number of wavelengths on each fiber is varied as $W = 24/F$ accordingly. We observed that six fibers per link in the ring and four fibers per link in the mesh-torus, are sufficient to provide similar performance as that in full-wavelength-convertible networks ($F = 24$, $W = 1$). We also observe that the full wavelength conversion ($F = 24$, $W = 1$) in the NSFnet does not improve much the performance compared to no wavelength conversion ($F = 1$, $W = 24$). It is also interesting to note that only four fibers per link is sufficient to provide similar performance as that of using full wavelength converters in the NSFnet.

An important conclusion is that a multifiber network has similar blocking performance as that of a full-wavelength-convertible network, if we select the wavelength-fiber-pairs adequately. A limited number of fibers is sufficient to guarantee high network performance. Thus, multifiber WDM networks without wavelength conversion is not only a feasible, but also a desirable choice under current technologies.

One can also use alternate routing mechanisms in multifiber systems. For example, in APR, a set of paths are pre-computed statically for each s–d pair and stored sequentially at the sources nodes according to specified criteria, e.g., the path length. Upon the arrival of a connection request at a source node, the paths are searched sequentially. The first path that has free wavelengths available is selected, and one wavelength is randomly selected to establish the connection. The request is blocked only if all of the candidate paths have no free wavelengths. Alternate-path routing improves the single-fiber network performance significantly. The same algorithms [15] can also be used for multifiber networks. We have observed that routing algorithms affect the benefits of using multiple fibers on each link in WDM networks. The number of fibers required to provide high performance using APR is slightly higher than that required using FPR. However, still, a limited number of fibers are sufficient to guarantee high performance.

V. COST MODEL

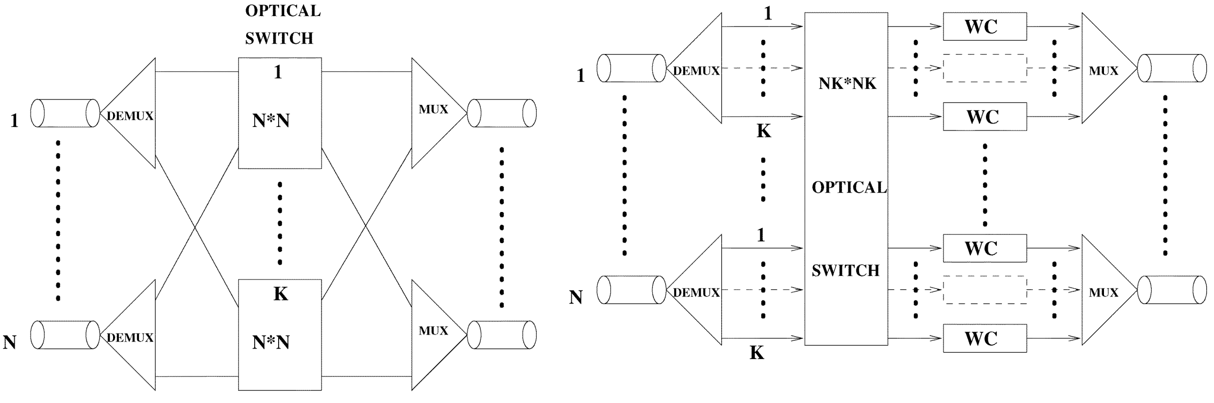
In Section IV, we introduced multiple fibers on each link as an alternate solution to overcome the wavelength continuity constraint. Using analysis and simulation results, we showed that a limited number of fibers per link are sufficient to guarantee that the network blocking performance is similar to that of networks with full wavelength conversion at every node. However, the cost of a multifiber network cannot be compared to a wavelength-convertible network without having a realistic cost model. In this section, we develop a parametric cost model for both multifiber networks and single-fiber wavelength-convertible WDM networks. By comparing the cost of different network configurations, we show that a multifiber network is a cost-effective solution with current technology.

A. Cost Parameters

We study a general network topology represented by $G(V, E, F, W)$, which shows that the network has $|V|$ nodes and $|E|$ links. We assume that every link has the same number of fibers per link, F, and the same number of wavelengths per fiber, W. We consider three cost factors in a WDM network: the cost related to: 1) a cable (C_{Cable} cost); 2) to a fiber (C_{Fiber} cost); and 3) to a switch (C_{Switch} cost).

Cable Cost: The cable cost, C_{Cable}, includes digging cost, leasing cost, right-of-way cost, and cable maintenance cost, etc., which are required before any capacity can be used on a link. Different link configurations, i.e., the number of fibers per link (F) and the number of wavelengths per fiber (W), do not affect the cable cost significantly. To simplify the cost comparison, we assume that the cable cost of a multifiber network is the same as that of a single-fiber wavelength-convertible network. Another assumption here is that either dark fibers are available ($C_{\mathrm{Cable}} = 0$) or new fibers have to be laid out in both multifiber and single-fiber networks.

Fiber Cost: The fiber cost, C_{Fiber}, is the combination of costs associated with fiber in a link. The fiber cost typically



(a) (b)

Fig. 3. Architecture of nodes (a) without and (b) with wavelength converters.

consists of the cost of physical fibers, OAs, dispersion compensation components, multiplexers and demultiplexers to terminate a fiber, and signal regenerators if installed in the network. Since we consider the fiber cost as a combination of the costs associated with the fiber, the number of wavelengths that a fiber carries affects the fiber cost significantly. One reason is that the components handling more wavelengths costs more than the components that handle fewer wavelengths. For example, a dispersion compensation component that can handle 64 wavelengths on each fiber will cost several times more than a compensation component that can only compensate the signals on a fiber consisted of 16 wavelengths. Another reason is that the power budget of OAs such as EDFA decreases with additional wavelengths. Consequently, we either have to increase the laser power or decrease the distance between two OAs. In either case, the cost of OAs for each fiber increases with the increasing number of wavelengths per fiber. Therefore, the number of wavelengths per fiber w has to be considered as a parameter in the fiber cost. We introduce a uniformed parameter $\bar{C}_{\mathrm{Fiber}}(w)$ to describe the fiber cost of a network. $\bar{C}_{\mathrm{Fiber}}(w)$ is defined as the cost of a fiber with one-unit length that carries w wavelengths. Let i be a link of the network $1 \leq i \leq |E|$. $\bar{C}_{\mathrm{Fiber}}(w)$ can be computed as

$$\bar{C}_{\mathrm{Fiber}}(w) = \frac{\sum_{i=1}^{|E|} C_{\mathrm{Fiber}}(i, w)}{\sum_{i=1}^{|E|} L(i)} \tag{1}$$

where $L(i)$ is the length of link i and $C_{\mathrm{Fiber}}(i, w)$ is the cost of the fiber with w wavelengths on link i. $C_{\mathrm{Fiber}}(i, w)$ is calculated by adding up all the cost associated with one fiber on link i. The total fiber cost of a multifiber network with parameters F and W is given by

$$C_{\mathrm{Fiber}}(F, W) = F \times \bar{C}_{\mathrm{Fiber}}(W) \times \sum_{i=1}^{|E|} L(i). \tag{2}$$

Switch Cost: Many components contribute to the cost of a switch C_{Switch}. To simplify the cost model of an optical switch, we consider two general switch architectures without and with wavelength converters, as shown in Fig. 3. Since the number of output ports for memuxes and input ports for muxes are same in two switches (for the scenarios we will consider for comparison), we ignore their costs. The actual cost depends on the architecture and technology used in each switch. We account for the cost of switching elements (C_{SE}) in a switch and the cost of wavelength converters (C_{conv}) if incorporated. Dedicated converters are used for each output for each wavelength in the switch as shown in Fig. 3(b). A converter can also be shared by multiple wavelengths. If so, the cost of a wavelength converter would also be shared.

We assume that the optical switch blocks at each node are nonblocking Batcher–Banyan switches made up of 2×2 switching elements. Let M_{WC} be the number of switching elements required by a node equipped with wavelength converters and N input fibers each with K wavelengths. M_{NWC} denotes the number of switching elements in a node with no wavelength converters and N input fibers each with K wavelengths. M_{WC} and M_{NWC} have been calculated in [7] and are as follows:

$$M_{\mathrm{WC}}(N, K) = \left(\frac{NK}{4}\right) \times (3 + \log_2 NK)(\log_2 NK) \tag{3}$$

$$M_{\mathrm{NWC}}(N, K) = \left(\frac{NK}{4}\right) \times (3 + \log_2 N)(\log_2 N). \tag{4}$$

Cost Difference: Our goal is to compare networks that have nodes with single-fiber input links and full wavelength conversion and multiple fibers input links and no wavelength conversion. To make a fair comparison for the case in hand, we fix the capacity on each link, that is the product of the number of fibers F in each link and the number of wavelengths W carried by each fiber, as constant denoted by D, i.e., $D = FW$. Notice that the number of output ports at demuxes and the number of input ports at muxes are same in the two cases and $M_{\mathrm{WC}} > M_{\mathrm{NWC}}$. Thus, a wavelength-convertible optical switch may cost more than a switch without wavelength conversion, not only because of the extra cost of converters, but also the cost of increased number of switching elements.

Let e_j denote the number of links connected to node j. Note the ($\sum_{j=1}^{|V|} e_j = 2|E|$. The switch cost $C_{\mathrm{Switch}-WC}$ for a single-fiber network with $|V|$ nodes, each equipped with wavelength conversion, can be computed by setting $N = e_j$ and $K = D$ for node j. The number of wavelength converters at node j is $D \times e_j$. The cost of consisting of two parts, switching elements and the converters, after ignoring the cost of demuxes and muxes is then given by

$$C_{\text{Switch}-WC} = C_{\text{SE}} \times \left(\sum_{j=1}^{|V|} M_{\text{WC}}(e_j, D) \right) + C_{\text{conv}} \times \left(\sum_{j=1}^{|V|} De_j \right). \quad (5)$$

The corresponding in a multifiber network without wavelength conversion is obtained by setting $N = e_j \times F$ (F fibers in each of the e_j links) and $K = D/F$ and is given by

$$C_{\text{Switch}-\text{NWC}} = C_{\text{SE}} \times \left(\sum_{j=1}^{|V|} M_{\text{NWC}} \left(Fe_j, \frac{D}{F} \right) \right). \quad (6)$$

Let C_{diff} be the cost difference between the cost of a single-fiber wavelength-convertible network and the cost of a multifiber network without wavelength conversion. Since, the cost of cable is the same in the two cases, we can divide the total cost difference into two parts: 1) fiber cost difference (C_{diff}^f); and 2) switch cost difference. The switch cost difference again consists of two parts, converters cost difference (C_{diff}^c) and SEs cost difference (C_{diff}^s). Then, the cost difference between a single-fiber wavelength-convertible network and a multifiber network, C_{diff}, is given by

$$C_{\text{diff}} = C_{\text{diff}}^f + C_{\text{diff}}^c + C_{\text{diff}}^s. \quad (7)$$

The three factors with the assumption that $\bar{C}_{\text{Fiber}}(D) = \gamma_{DW} \times \bar{C}_{\text{Fiber}}(W)$ are as follows:

$$\begin{aligned} C_{\text{diff}}^f &= \sum_{i=1}^{|E|} \left(\bar{C}_{\text{Fiber}}(D) - F \times \bar{C}_{\text{Fiber}} \left(\frac{D}{F} \right) \right) \times L(i) \\ &= (\bar{C}_{\text{Fiber}}(W)) \times (\gamma_{DW} - F) \times \left(\sum_{i=1}^{|E|} L(i) \right) \qquad (8) \end{aligned}$$

$$C_{\text{diff}}^c = C_{\text{conv}} \times \left(\sum_{j=1}^{|V|} De_j \right) - 0 = 2 \times C_{\text{conv}} \times D \times |E| \quad (9)$$

$$\begin{aligned} C_{\text{diff}}^s &= C_{\text{SE}} \times \sum_{j=1}^{|V|} M_{\text{WC}}(e_j, D) - M_{\text{NWC}} \left(Fe_j, \frac{D}{F} \right) \\ &= C_{\text{SE}} \times \left(\sum_{j=1}^{|V|} \left(e_j \frac{D}{4} \right) \times (3 + \log_2(e_j e_j DF)) \right. \\ &\quad \left. \times \left(\log_2 \left(\frac{D}{F} \right) \right) \right). \qquad (10) \end{aligned}$$

We can clearly see the tradeoff of using multiple fibers in each link or wavelength converters in an optical switch to improve the network performance from the above analysis. Since it can be expected that $\gamma_{DW} < F$ we know from (8) that $C_{\text{diff}}^f < 0$.

TABLE I

LINK LENGTHS IN MILES IN NSFNET

Link	Length	Link	Length	Link	Length
NY - MD	375	NY - MI	643	NY - PA	286
NJ - MI	860	NJ - MD	160	NJ - PA	235
MD - TX	1603	PA - IL	710	PA - GA	883
IL - NE	678	MI - UT	1788	NE - CO	428
GA - TX	1111	CO - TX	813	CO - UT	475
CA2 - CA1	345	TX - CA2	1565	CA2 - WA	986
WA - IL	2031	WA - CA1	1000	UT - CA1	775

TABLE II

LINK LENGTHS IN MILES IN NJLATA NETWORK

Link	Length	Link	Length	Link	Length
SC-SB	28.33	SC-CL	31.00	CL-SB	51.00
CL-TR	27.67	SB-HC	21.00	SB-TR	64.67
SB-LW	64.00	SB-WB	97.33	HC-TR	48.67
HC-LW	43.33	TR-AP	38.00	TR-LW	29.00
TR-AC	60.00	TR-BG	58.33	TR-WB	32.67
AP-LW	14.00	LW-AC	50.00	LW-BG	67.67
LW-WB	50.33	AC-BG	41.00	AC-CM	35.67
BG-CM	35.33	BG-WB	27.67		

TABLE III

LINK LENGTHS IN MILES IN NATIONALNET NETWORK

Link	Length	Link	Length	Link	Length
WA-UT	669	WA-MT	467	WA-OR	136
MN-NE	162	MN-IL	329	MN-MT	877
NE-3	167	NE-IN	511	KS-IN	444
KS-OK	283	KS-UT	891	KS-MT	966
IN-IL	164	IN-GA	418	IN-OK	663
IN-DC	479	IL-MI	231	GA-OK	744
GA-DC	531	GA-NC	346	GA-FL	614
GA-TX1	710	OK-UT	845	OK-TX1	363
OK-TX2	188	OK-NM	513	UT-MT	387
UT-NM	473	UT-ID	288	MI-MA	597
MI-DC	387	MA-DC	381	DC-NC	231
NC-FL	698	FL-TX1	1001	TX1-TX2	185
TX2-NM	586	NM-AZ	312	NM-ID	762
AZ-CA1	361				

Equation (10) shows that $C_{\text{diff}}^s > 0$. The cost of the converter is of course additional in a single-fiber wavelength-convertible network. To compute the cost difference numerically, we need to unify the cost factors. We choose $\bar{C}_{\text{Fiber}}(W)$ and C_{conv} as base cost units.

VI. NUMERICAL RESULTS

We studied the blocking performance of the NSFnet in the previous section. Here, we study the cost issue of three different networks: NSFnet, NJLATA, and NationalNet [21]. Our goal is to see the tradeoff of using multiple fibers per link over single fiber network with wavelength conversion. The NSFnet consists of 14 nodes and 21 links, i.e., $|V| = 14$ and $|E| = 21$. The length of each link $L(i)$ for $i = 1, \ldots, 21$, is shown in Tables I–III. The link length is assumed to be the driving distance between the two nodes. Among the 14 nodes in the NSFnet, 10 nodes have input/output degrees $e_j = 3$, 2 nodes have $e_j = 4$, and 2 nodes have $e_j = 2$.

In the numerical calculation, for simplicity, we assume that the link capacity is fixed at 32, i.e., $D = 32$. In the multifiber configuration of the NSFnet we studied, we fix the number of fibers per link at 4, i.e., $F = 4$, and correspondingly, the number of wavelengths per fiber is $W = 8$. Using these parameters and the node degree for the NSFnet nodes, we obtain

$$\begin{aligned} C_{\text{diff}}^{f} &= (\bar{C}_{\text{Fiber}}(W)) \times (\gamma_{DW} - F) \times \left(\sum_{i=1}^{|E|} L(i) \right) \\ &= 17\,750 \times (\gamma_{DW} - 4) \times \bar{C}_{\text{Fiber}}(8) \\ C_{\text{diff}}^{c} &= C_{\text{conv}} \times \left(\sum_{j=1}^{|V|} De_j \right) - 0 = 1344 \times C_{\text{conv}} \\ C_{\text{diff}}^{s} &= C_{\text{SE}} \times \left(\sum_{j=1}^{|V|} \left(e_j \frac{D}{4} \right) \times (3 + \log_2(e_j e_j DF)) \right. \\ &\qquad \left. \times \left(\log_2 \left(\frac{D}{F} \right) \right) \right) = 13\,320 \times C_{\text{SE}}. \end{aligned} \tag{11}$$

The overall cost difference between the two designs is

$$\begin{aligned} C_{\text{diff}} = 17\,750 \times (\gamma_{DW} - 4) \times \bar{C}_{\text{Fiber}}(8) \\ +1344 \times C_{\text{conv}} + 13\,320 \times C_{\text{SE}}. \end{aligned} \tag{12}$$

Similarly, using the data for the other two networks which were discussed earlier, the following two are our findings for the networks NJLATA and NATIONALNET as given in (13) and (14), respectively:

$$\begin{aligned} C_{\text{diff}} &= 1016.67 \times (\gamma_{DW} - 4) \times \bar{C}_{\text{Fiber}}(8) \\ &\quad + 1472 \times C_{\text{conv}} + 15\,949.47 \times C_{\text{SE}}. \end{aligned} \tag{13}$$

$$\begin{aligned} C_{\text{diff}} &= 20648 \times (\gamma_{DW} - 4) \times \bar{C}_{\text{Fiber}}(8) \\ &\quad + 2816 \times C_{\text{conv}} + 29\,522 \times C_{\text{SE}}. \end{aligned} \tag{14}$$

The cost of a unit-length fiber with W wavelengths on it ($\bar{C}_{\text{Fiber}}(W)$) depends on many factors, e.g., the technologies used for OAs and the fibers used that may or may not require dispersion compensation etc. The cost may thus vary significantly in different cases. Similarly, the cost of a wavelength converter, C_{conv}, may also vary depending on what technologies are developed. If we assume that the cost ratio of a fiber with 32 wavelengths to a fiber with 8 wavelengths, γ_{DW}, is 2, and C_{SE} is 100 times cheaper than C_{conv}[1], i.e., $C_{\text{SE}} = 0.01 \times C_{\text{conv}}$, then we know from (12) that the overall cost difference between the two network configurations is zero if C_{conv} is about 25 times of $\bar{C}_{\text{Fiber}}(8)$. For the same values of γ_{DW} and $C_{\text{SE}} = 0.01 \times C_{\text{conv}}$, the ratio of C_{conv} to $\bar{C}_{\text{Fiber}}(8)$ is 1.3 and 13.3 for NJLATA and NATIONALNET, respectively, from (12) and (12). respectively. Consequently, the results show that with more expensive converters, the multifiber networks are a better choice.

As can be seen from the above results, a sparse network works better without converters when C_{conv} to $\bar{C}_{\text{Fiber}}(8)$ is about 25. However, for dense networks, multifiber option is better even when this ratio is small.

New technologies of installing fibers in MANs and LANs have been developed to reduce the fiber cost. In these networks, OAs may not be required because of the short distance between any two nodes. Therefore the fiber cost may not play a significant role in the overall network cost in MANs and LANs. Moreover, the technologies for wavelength conversion are not mature yet. The cost of wavelength converters is likely to remain high in the near future. Thus, multifiber networks are a cost-effective solution and attractive option even for WANs.

VII. CONCLUSIONS AND FUTURE WORK

WDM technology has revolutionized the WAN by enabling huge increase in the capacity of a single fiber. Wavelength-routed all-optical networks cost-effectively improve the scalability, flexibility, and reliability of not only backbone networks, but also MANs and LANs.

Different technologies of converting one wavelength to another wavelength have been demonstrated in laboratories. However, none of these are really commercially available yet. The cost of an all-optical wavelength converter is likely to remain high in the near future. The multifiber WDM network is an alternative solution to conquer the wavelength continuity constraint. In multifiber WDM networks, a wavelength that cannot continue on the next hop can be switched to another fiber using an OXC if the same wavelength is free on one of the other fibers. We study the effect of multiple fibers in all- optical WDM networks. The results show that a multifiber network has similar blocking performance as that of a full-wavelength-convertible network, if we select the wavelength-fiber pairs adequately. A limited number of fibers are sufficient to guarantee high network performance. We also demonstrate that a multifiber network is a cost-effective solution. Finally, it should be noted that an additional advantage of utilizing multifiber solutions is the single fiber failure fault tolerance capability of the system.

ACKNOWLEDGMENT

The authors would like to thank N. Jose for his help in generating some of the data and tables.

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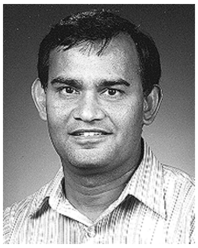

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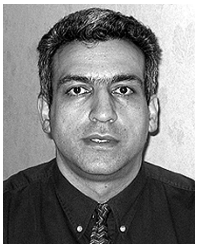

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