Research Article

The Gain of Performance of Optical WDM Networks

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We study the blocking probability and performance of single-fiber and multifiber optical networks with wavelength division multiplexing (WDM). We extend the well-known analytical blocking probability model by Barry and Humblet to the general model, which is proposed for both single-fiber and multifiber network paths with any kind of wavelength conversion (no, limited, or full wavelength conversion) and for uniform and nonuniform link loads. We investigate the effect of the link load, wavelength conversion degree, and the number of wavelengths, fibers, and hops on blocking probability. We also extend the definition of the gain of wavelength conversion by Barry and Humblet to the gain of performance, which is fully general. Thanks to this definition and implementation of our model, we compare different WDM node architectures and present interesting results.

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1. INTRODUCTION

Thanks to the latest technological advances in optical technology in recent years, optical networks based on wavelength division multiplexing (WDM) technology are a very attractive solution to satisfy the current bandwidth requirements of the internet infrastructure. Moreover, they promise to provide a scalable solution to support the bandwidth needs of future applications. Hybrid WDM/OTDM networks are mainly supposed to be implemented in future long-haul networks. Under the difficult competitive open business environment in these days, a certain quality of service provided to the customer is required for the implementation of WDM networks into the real network infrastructure. The main focus of network operators is to optimize their networks and to achieve an optimal compromise between economic costs and quality of services. Hence interest in the dimensioning and provisioning of WDM networks is still a really up to date research subject.

The aim of this article is to study optical WDM networks in terms of blocking probability and performance gain. The paper is structured as follows. Section 2 briefly introduces WDM optical networks. We propose our general blocking probability model and present its simulation results in Section 3. We define gain of performance and compare

different WDM node architectures in Section 4. Finally, the conclusion and future work remarks are given in Section 5.

2. WDM NETWORKS

The all-optical (photonic) networks enable switching and routing functions at the optical layer. The optical signal still remains in the optical domain between two access nodes and the latencies induced by optoelectronic conversions at intermediate nodes disappear. In all-optical networks, different types of multiple user technology can be used: OTDM (optical time division multiplex), CDM (code division multiplex), or WDM (wavelength division multiplex). WDM is the favorite choice because both CDM and OTDM are still limited by fiber physical characteristics and the state of optical technology, especially due to the difficult synchronization requirements.

Optical networks, which employ wavelength division multiplex (WDM) technology, are called *WDM networks*. They provide simultaneous transmission on a few different optical wavelengths through the same optical fiber. However, thanks to many connections simultaneously shared on the same fiber, the huge bandwidth potential of optical fiber is much better utilized. This allows different end-users to operate at electronic processing speeds, which are still limited

to about 40 Gb/s. Moreover, each connection established between the end nodes on a WDM channel enables the specification of a different bit rate and data format. This is referred to as *WDM transparency*. All connections using the same fiber link must allocate different and distinct wavelengths. It is also known as *distinct wavelength assignment constraint*.

The proposed model is designed for wavelength routed optical networks based on optical channel switching. Such networks consist of two types of nodes:

- (i) optical cross-connects (OXC) equipped with a few input and output ports, which are connected to other OXC or optical access nodes by optical fibers;
- (ii) end nodes (access nodes), which provide the interface between nonoptical end and optical systems.

The OXC can be fitted with an optical converter to provide optical conversion in the optical domain. If an OXC does not support any wavelength conversion, the same wavelength must be used on next hop of the path. This is known as *wavelength continuity constraint* [1]. If all network OXC do not support any wavelength conversion, the same wavelength must be used on all the fiber links along the physical path. Such a network is called a *no wavelength conversion network* [1]. A connection request is accepted only if there is at least one wavelength which is simultaneously free on all the links along the path. This means that a call can be blocked even if there are free wavelengths on all the links, but they are not all the same.

The maximum number of wavelengths is still limited by optical device technology, the total available bandwidth, the component spectral range, and the spacing between channels. Hence wavelength reuse is required by a wavelength conversion in OXC. If an OXC enables a wavelength conversion, a different wavelength can be assigned on the next path hop. If each OXC supports full wavelength conversion, this is referred as a *full wavelength conversion network*. A connection request is accepted if there is at least one free wavelength on each fiber link along the path.

Full wavelength conversion in the optical domain improves network blocking performance significantly [1]. Unfortunately, the employment of full wavelength conversion all-optical converters in each network node greatly increases the network cost due to the complexity of the optical device technology. The aim of researchers is to achieve high or similar network performance by a limited range of wavelength conversion for each converter, a limited number of converters in each OXC, and a limited number of OXC supporting wavelength conversion in the whole network. Another possibility to relax the wavelength continuity constrain is to implement multifiber links.

2.1. Limited wavelength conversion networks

If a network supports wavelength conversion with some restrictions, it is called a *limited wavelength conversion network*. These restrictions can be as follows [2]:

- (i) *a limited range of wavelengths to which an input wavelength may be converted*. If any incoming wavelength can be converted to any wavelength from a limited set

of k outgoing wavelengths on the output side of wavelength spectrum plane W , it is referred to as *limited wavelength conversion with conversion degree k* ;

- (ii) *a limited number of wavelength converters are placed at each node*. This is also known as *partial wavelength conversion*. A wavelength converter bank consisting of a collection of a few wavelength converters is shared. Share-per-node and share-per-link wavelength-convertible switch architectures have been proposed [1];
- (iii) *a limited number of nodes enabling wavelength conversion are placed in the network*. If only a few network nodes enable a wavelength conversion, not all, this is called a *sparse wavelength conversion* [1].

Two first limitations mentioned above are implemented in the network nodes and last one is based on network restriction. The network costs can be decreased by using converters with a limited range of wavelength conversion rather than full range conversion, assuming a limited number of converters in each node and a limited number of conversion nodes in the network rather than enabling wavelength conversion in each network node. However, placement of converters in a network, allocation of converters in a node, and specification of wavelength conversion range issues are raised. Recent research has shown that limited conversion is much easier and cheaper than full conversion. Moreover, limited wavelength conversion networks are still able to provide enough conversion to use channels efficiently, and at much better channel efficiency than no wavelength conversion networks, depending on the design.

Unfortunately, the detailed explanation of each limited wavelength conversion scenario is outside the scope of this paper. However, it can be found in [2]. We only discuss the first case of limited wavelength conversion in more detail.

In general, for limited wavelength conversion with conversion degree k , any incoming wavelength λ_i , $i \in W$ can be converted to any wavelength λ_j , $j \in k$ from a limited set of k ($1 < k < W$) outgoing wavelengths on the output side of the wavelength spectrum plane W [2]. In practice, the following types of limited wavelength conversion are used:

- (i) *symmetrical*: any incoming wavelength can be converted to any wavelength from d adjacent outgoing wavelengths on the left and right side of the wavelength plane of the spectrum, as well as the same wavelength. This means that any incoming wavelength can be converted to one from $k = 2d + 1$ outgoing wavelengths;
- (ii) *nonsymmetrical*: any incoming wavelength can be converted to the same wavelength or to one on the left (or the right) side of the wavelength plane. This means that it is possible to switch any incoming wavelength to a wavelength from $k = d + 1$ outgoing wavelengths.

Note that the conversion capability of the optical OXC can be classified into three types depending on their range of wavelength conversion k :

- (i) $k = 1$, no wavelength conversion capability;
- (ii) $1 < k < W$, limited wavelength conversion capability;
- (iii) $k = W$, full wavelength conversion capability.

2.2. Multifiber networks

Networks that employ bundles of fibers between the network nodes are called *multifiber networks*. In multifiber WDM networks, each link consists of multiple fibers and each fiber carries information on multiple wavelengths [3]. Generally, each network link can consist of a different number of fibers F , and each fiber can use a different number of wavelengths W .

Thanks to decreasing fiber costs in recent years, current research tends toward the multifiber networks. In fact, most of the optical networks deployed to date, employ multiple fibers between end nodes due to the economic advantage of installing bundles of fibers for the purposes of fault tolerance and future network growth. Performance improvement, in terms of blocking probability and throughput, can be achieved by using these fibers or adding more fibers to the existed system.

Theoretically, multifiber WDM networks can be implemented with no, limited, or full wavelength conversion. However, the benefit of using no wavelength conversion multifiber networks is important. If a wavelength cannot continue on the next hop on the same fiber, and the same wavelength is available on any other fibers on the next hop, then the incoming wavelength can be switched to another fiber. Thus the functionality of a multifiber network with F fibers per link and W wavelengths per fiber is equivalent to a limited wavelength conversion of degree F single-fiber network, with $F \cdot W$ wavelengths [1, 3].

The design aim of a multifiber network is to decide how many fibers per link are required to guarantee high network performance or to achieve high network performance with the minimum number of fibers per link.

3. THE ANALYSIS OF PATH BLOCKING PROBABILITY

The proposed model is derived from the model by Barry and Humblet taking into consideration the type of wavelength conversion and the multifiber network scenario and, hence, is general.

3.1. Assumptions and notations

Three independence assumptions are considered, which generally lead to the overestimation of blocking probability:

- (i) link independence assumption: the link states on different links are independent [4];
- (ii) wavelength independence assumption: the individual wavelengths are utilized independently of the utilizations of other wavelengths on the same link [4];
- (iii) fiber independence assumption: the fiber is utilized independently.

The blocking probability analysis is simpler due to the factors above, but the model is not very accurate. However, the computational complexity of the model is moderate. In this paper, the following parameters and notations are used:

- (i) W : number of wavelengths on each link per fiber;
- (ii) H : number of hops along a path;
- (iii) F : number of fibers per hop;

- (iv) N : number of network nodes;
- (v) Ch : number of channels in a hop; $Ch = W \cdot F$;
- (vi) $l_{i,j}$: direct link between directly consecutive node i and j ;
- (vii) $a^{n,m}$: end-to-end traffic load on a path from node n to node m ;
- (viii) $a_{i,j}^{n,m}$: amount of traffic $a^{n,m}$ going through link $l_{i,j}$;
- (ix) $\rho_{i,j}$: load per wavelength over link $l_{i,j}$;
- (x) R : network path, that is, consecutive links $l_{i,j}$ between access nodes n, m ;
- (xi) No: no wavelength conversion capability;
- (xii) Lim: limited wavelength conversion capability;
- (xiii) Full: full wavelength conversion capability.

We consider the single-fiber and multifiber wavelengths routed optical networks based on optical channel switching (Figure 1). The network path R is defined as a set of consecutive links $l_{i,j}$, between any two end nodes n, m . This consists of H hops and N nodes.

In the model, it is assumed that the call request arrives on each link as a Poisson process with arrival rate λ and that the connection holding time is exponentially distributed with service rate μ . Hence the load is expressed as $a = \lambda/\mu$. The wavelength utilization (load per wavelength) ρ is the probability that a wavelength is used on a link on the fiber. Following the traffic model in [4], the load per wavelength between any two access nodes n, m on a link $l_{i,j}$ can be expressed by

$$\rho_{i,j} = \frac{\sum_{n,m} a_{i,j}^{n,m}}{W}. \quad (1)$$

The sum $\sum_{n,m} a_{i,j}^{n,m}$ expresses the traffic load contributions from all the end-to-end originating demands passing through the relevant $l_{i,j}$. If there is the same link load over all links (i.e., $\rho_{i,j} = \rho$), this is referred to as *uniform link load*. Otherwise, this is known as *nonuniform link load*.

In general, each network link can consist of a different number of fibers F and each fiber may have a different number of wavelengths W . However, in our model we assume the same number of fibers on all network links and the same number of wavelengths on each network fiber.

3.2. The proposed analytical blocking probability model

The proposed model is designed to compute the end-to-end blocking probability between any pair of network nodes n, m along the path R , of both single-fiber and multifiber WDM networks with any range of wavelength conversion (no, Limited, or full wavelength conversion) with regard to independence, traffic, and network assumptions mentioned above. The model presents the blocking probability as a function of the load ρ , the wavelength conversion degree k , the number of wavelengths W , the number of hops H , and the number fibers F .

The blocking probability $P_{b,WDM}$ of WDM optical network path R is the probability that, for each wavelength, there is at least one hop of the path on which all wavelengths from

FIGURE 1: WDM network. (a) The model of a single-fiber WDM network ($F = 1$). (b) The physical network path between nodes A, B consists of 3 hops and 4 nodes ($N = 4$, $H = 3$). The network is modeled as a directed graph. (c) The optical domain consists of 3 wavelengths (λ_1 , λ_2 , and λ_3) on each link ($W = 3$).

TABLE 1: The blocking probability model for uniform link load.

	Single-fiber WDM network path $F = 1$	Multifiber WDM network path $F > 1$
No ($k = 1$)	$P_{b, \text{no}} = [1 - (1 - \rho)^H]^W$ (2a)	$P'_{b, \text{no}} = [1 - (1 - \rho^F)^H]^W$ (2d)
Full ($k = W$)	$P_{b, \text{full}} = 1 - (1 - \rho^W)^H$ (2b)	$P'_{b, \text{full}} = 1 - (1 - \rho^{F \cdot W})^H$ (2e)
Lim ($1 < k < W$)	$P_{b, \text{lim}} = [1 - (1 - \rho^k)^H]^{W/k}$ (2c)	$P'_{b, \text{lim}} = [1 - (1 - \rho^{F \cdot k})^H]^{W/k}$ (2)

a set of wavelengths k are used on all fibers. For uniform link load, this is expressed as

$$P_{b, \text{WDM}} = [1 - (1 - \rho^{F \cdot k})^H]^{W/k}, \quad (2)$$

and for nonuniform link load, this is derived as follows:

$$P'_{b, \text{WDM}} = \left[1 - \prod_{i,j \in R; H} (1 - \rho_{i,j}^{F \cdot k}) \right]^{W/k}. \quad (3)$$

The uniform link load model is derived as follows: note that ρ is the probability that a wavelength is used on a hop. Then ρ^k expresses the expected probability that all k wavelengths, on which any incoming wavelength can be converted, are occupied on the hop. For the F fibers hop, the expected probability that all k wavelengths on each fiber are occupied is ρ^{kF} . The probability that a suitable wavelength is free on a hop is $1 - \rho^{kF}$. Hence the probability that a suitable wavelength is free on all hops along its path is $(1 - \rho^{kF})^H$. The factor W/k represents the effect of limited wavelength conver-

sion with conversion degree k . It is supposed that the waveband W is split to a few subwavebands W/k depending on the conversion degree. Any connection using a wavelength from any subwaveband is supposed not to change this subwaveband along the optical path between end nodes. The factor W/k expresses the number of possibilities in which the limited set of wavelengths k from waveband W , can be divided. Note that this is an analytical model. In real configurations, W/k can only be an integer.

Note also that depending on the conversion degree k , the proposed models (2) and (3) are general for no ($k = 1$), limited ($1 < k < W$), and full ($k = W$) wavelengths conversion networks. Depending on the number of fibers F , the model is also valid for single-fiber ($F = 1$) and multifiber ($F > 1$) network paths. Hence the proposed model is general and is valid for any type of wavelength conversion and for any number of fibers. The model overview of uniform link load is presented in Table 1, and the model overview of nonuniform load is published in [6]. The model for any type of wavelength conversion of single-fiber network paths (2c) was presented for the first time in [5]. Note that for single-fiber network paths,

if no wavelength conversion is considered then $k = 1$ and the expression (2) can be modified to the model by Barry and Humblet without wavelength conversion (2a) also presented in [4]. Similarly, for full wavelength conversion ($k = W$), the proposed model (2) can be changed to the model by Barry and Humblet with full wavelength conversion (2b) published in [4].

The nonuniform link load model can be easily extended from the uniform link load model by taking into consideration the link load independence assumptions (see Section 3.1).

Taking into consideration both link and wavelength load independence assumptions, the blocking probability of any arbitrary WDM network can be determined as follows: a network can be divided into the corresponding number of particular network paths R , between each two access nodes in line with the routing algorithm. The corresponding amount of the traffic $a_{i,j}$ going through link $l_{i,j}$ on each network path R , is given by (1). The blocking probability $P_{b,WDM}^{n,m}$ of each network path can be computed by using (2) or (3). Then following [1] the overall blocking probability B of the network can be formulated as

$$B = \frac{\sum_{n,m} a_{n,m} P_{b,WDM}^{n,m}}{\sum_{n,m} a_{n,m}}. \quad (4)$$

The accuracy of the proposed model is assumed to be similar to the model by Barry and Humblet because the same assumptions are used. The problem of model accuracy is exhaustively presented in [4] and, unfortunately, it is outside the scope of this paper.

3.3. Numerical results of the proposed blocking probability model

All simulation results presented in this section are realized in a Matlab environment. The results are presented only for network paths as depicted in Figure 1(b). Different types of wavelength conversion (no, limited, and full) and single-fiber and multifiber scenarios are considered.

In Figures 2 and 3, the blocking probability of no, full, and limited wavelength conversion network paths is plotted as a function of wavelength utilization ρ for single-fiber and multifiber network paths, respectively. For both single-fiber and multifiber scenarios, the number of wavelengths is $W = 15$ and the degree of limited wavelength conversion is $k = 3$. The single-fiber path is plotted for $H = 10, 20$ hops and multifiber path is drawn for $H = 20, 40$ hops and $F = 15$ fibers. As can be seen from both figures, the blocking probability increases with the wavelength utilization ρ and the number of hops H . Note that the wavelength conversion reduces the blocking probability and, thus, increases wavelength utilization ρ .

In Figure 4, the blocking probability of no, limited, and full wavelength conversion single-fiber network paths is plotted as a function of the number of hops H for $W = 10, 20$ wavelengths, $\rho = 0.2$, and $k = 3$. As expected, the blocking probability increases as the number of hops increases. The blocking probability of no wavelength conversion network

FIGURE 2: The blocking probability $P_b = f(\rho)$, $W = 15$, $k = 3$, and $F = 1$.

FIGURE 3: The blocking probability $P_b = f(\rho)$, $W = 15$, $k = 3$, and $F = 15$.

paths depends on the number of hops, significantly unlike limited or full wavelength conversion scenario. The effect of the path length is really dramatic for no wavelength conversion.

Figure 5 shows the blocking probability of a single-fiber network path as a function of the conversion degree k for $W = 20$, $\rho = 0.5$, and $H = 5, 10, 20$ hops. Note that when no wavelength conversion is considered, k equals 1 and for full wavelength conversion, the conversion degree k is equal to W . From the figure, the proper conversion degree can be estimated. As k increases at the beginning,

FIGURE 4: The blocking probability $P_b = f(H)$, $\rho = 0.2$, $k = 3$, and $F = 1$.

FIGURE 6: The blocking probability $P_b = f(F)$, $\rho = 0.8$, $W = 10$, and $k = 3$.

FIGURE 5: The blocking probability $P_b = f(k)$, $\rho = 0.5$, $W = 20$, and $F = 1$.

the blocking probability rapidly decreases. After a point, the blocking probability slowly decreases as the conversion degree increases. The performance improvement of limited wavelength conversion with small conversion degree is considerable, compared with the no wavelength conversion performance, as shown in Figure 5.

Similar results can be obtained for multifiber networks. Unfortunately, detailed explanation and graphic presentation of the results of multifiber scenarios are beyond the

scope of this paper. However, they are described quite exhaustively in [6].

The blocking probability as a function of the number of fibers for no, limited, and full wavelength conversion and for $W = 10$, $\rho = 0.8$, and $k = 3$ is plotted in Figure 6. It can be clearly seen that the blocking probability decreases significantly as the number of fibers increases.

The results of the proposed model are briefly summarized as follows:

- (i) the blocking probability always increases with the wavelength utilization ρ and number of hops H ;
- (ii) the blocking probability decreases with the wavelength conversion degree k , the number of wavelengths W , and the number of fibers F ;
- (iii) the blocking probability of a no wavelength conversion network path dramatically increases with the number of hops H , in contrast to the network path with wavelength conversion;
- (iv) no wavelength conversion multifiber paths perform in very similar fashion to the limited wavelength conversion single-fiber paths, in terms of blocking probability;
- (v) for given parameters ρ , H , and W no wavelength conversion single-fiber paths achieve the highest blocking probability and full wavelength conversion multifiber paths achieve the lowest blocking probability;
- (vi) limited wavelength conversion paths present continual transition from no ($k = 1$) to full ($k = W$) wavelength conversion paths in terms of throughput, dependent on the conversion degree ($1 < k < W$);
- (vii) the performance of limited wavelength paths with small values of the conversion degree is very close to

TABLE 2: Overview of the gain of performance.

Gain of	Expression	Equal parameters	Different parameters
Performance	$G = \rho_{N1}/\rho_{N2} \big _{P_b, H}$	—	$F_{N1} \neq F_{N2}, W_{N1} \neq W_{N2}, k_{N1} \neq k_{N2}$
Wavelength conversion	$G_k = \rho_{N1}/\rho_{N2} \big _{P_b, H, F, W}$	$F_{N1} = F_{N2} = F,$ $W_{N1} = W_{N2} = W$	$k_1 \neq k_2$
Using multiple fibers	$G_F = \rho_{N1}/\rho_{N2} \big _{P_b, H, W, k}$	$W_{N1} = W_{N2} = W,$ $k_{N1} = k_{N2} = k$	$F_{N1} \neq F_{N2}$
Using multiple wavelengths	$G_W = \rho_{N1}/\rho_{N2} \big _{P_b, H, F, k}$	$F_{N1} = F_{N2} = F,$ $k_{N1} = k_{N2} = k$	$W_{N1} \neq W_{N2}$

the blocking performance of full wavelength conversion paths, for both single-fiber and multifiber network path scenarios, respectively.

4. THE GAIN OF PERFORMANCE

In this section, we extend the gain of wavelength conversion by Barry and Humblet [4] to the gain of performance of optical WDM networks. Thanks to this definition, any two different optical network path scenarios $N1, N2$ can be compared. The gain of performance is defined as the increase in wavelength utilization for the same blocking probability. It is expressed as the ratio between wavelength utilization (ρ_{N1}, ρ_{N2}) of two different optical network path scenarios, for the same blocking probability P_b and the number of hops H :

$$G = \frac{\rho_{N1}}{\rho_{N2}} \bigg|_{P_b, H}, \quad (5)$$

where the wavelength utilization of each network path can be expressed in terms of the blocking probability (2) as follows:

$$\rho = \left[1 - (1 - P_b^{k/W})^{1/H} \right]^{1/(F \cdot k)}. \quad (6)$$

It is assumed that the wavelength utilization ρ_{N1} belongs to the network path with the higher wavelength utilization, and that the utilization ρ_{N2} belongs to the network path with the lower wavelength utilization. Then ρ_{N1} is equal to or higher than ρ_{N2} . Hence the performance gain G is equal to or higher than 1.

In general, the gain of performance can be determined for any two arbitrary WDM optical network paths. In fact, the gain of performance expresses the gain by using network path $N1$ instead of network path $N2$. If the number of fibers F and wavelengths W are the same for both compared optical network paths, we can speak about the *gain of wavelength conversion* G_k instead of the gain of performance [2] because only the wavelength conversion degree is different. Thus the full wavelength conversion network path ($k = W$) can be compared with limited ($1 < k < W$) or no ($k = 1$) wavelength conversion network path. If the number of wavelengths W and the conversion degree k are the same for both optical network paths, this can be expressed as the *gain of using multiple fibers* G_F or gain of multifiber network paths.

Thanks to this, the multifiber ($F_{N1} > 1$) and single-fiber ($F_{N2} = 1$) network paths or two different multifiber network paths ($F_{N1} > 1, F_{N2} > 1$) can be compared to each other. Finally, if the number of fibers F and the conversion degree k are the same, the *gain of the using multiple wavelengths* G_W (or the gain of multiwavelength network paths) is defined. Thus, for example, two network paths with different numbers of wavelengths (W_{N1}, W_{N2}) can be compared. All these definitions are summarized in Table 2.

4.1. Numerical results of the performance gain

The gain of performance enables to comparison of the wavelength utilization between two different optical network path scenarios. Typical graphical characteristics of the performance gain G versus the number of wavelengths W are plotted in Figures 7–10 for blocking probability $P_b = 10^{-3}$. The results are presented only for network path as is depicted in Figure 1(b).

The typical characteristics of the gain of wavelength conversion G_W , which are presented in [4], only compare full with no wavelength conversion of single-fiber network path. According to this, the wavelength utilization is better for the full wavelength conversion network, in contrast to the no wavelength conversion network. The performance gain of this case is rather high, for example, it is still higher than 4 for $2 < W < 50$ and $H = 10$. This figure also shows that the gain G increases as the number of hops H increases quite considerably.

In Figure 7, the gain of wavelength conversion G_W of the full and no wavelength conversion scenario is plotted for multifiber network paths. From the beginning, as the number of wavelengths W increases, the gain G_W increases quite dramatically and almost linearly. The maximum peak of gain G_W is somewhere near $W = H/2$ based on observation. After that, the gain G_W slowly decreases and the convergence of the gain $G_W = 1$ is extremely slow for $W \rightarrow \infty$.

It can be seen from Figure 7 that the gain of this scenario is really small, for example, it is still lower than $G_W < 1.2$ for any number of the wavelengths (although the figure is plotted only for $W < 50$) and $H = 10$ hops. This is due to the fact that, although the no wavelength conversion multifiber network path provide no wavelength conversion, a different fiber may be used on each subsequent hop. Hence the

FIGURE 7: The gain of wavelength conversion $G_W = f(W)$, $P_b = 10^{-3}$, $F = 10$, and Full/No.

FIGURE 9: The gain of wavelength conversion $G_W = f(W)$, $P_b = 10^{-3}$, $F = 10$, $k = 3$, and Lim/No.

FIGURE 8: The gain of wavelength conversion $G_W = f(W)$, $P_b = 10^{-3}$, $F = 1$, $k = 3$, and Lim/No.

performance of the no wavelength conversion multifiber network paths is quite similar to the performance of the limited wavelength conversion single-fiber network paths. Also it can be seen from this figure that the effect of the number of hops is not very significant.

In Figures 8 and 9, the gain of wavelength conversion G_W of the limited ($k = 3$) and no wavelength conversion scenarios is plotted for both single-fiber and multifiber network paths, respectively. If the number of wavelengths is smaller than or equal to the conversion degree $W \leq k$, the limited wavelength conversion network path performs the same as

the full wavelength conversion network path. Therefore, at the beginning, the curves are exactly the same as in the previous case. The gain G_W increases quite dramatically as the number of wavelengths W increases. The peak value of gain G_W is for $W = k$. After that, gain G_W decreases and the convergence of gain $G_W = 1$ is quite slow for $W \rightarrow \infty$.

It can be seen from Figure 8 that the gain is still rather high, but not as high as the gain of full instead of no wavelength conversion optical single-fiber path scenario presented in [4], for example, $G_W > 2.5$ for $1 < W < 50$, $H = 10$, and $k = 3$. It can be observed for the multifiber network path scenario in Figure 9, that the curves are very similar, again. However, the gain is really poor, for example, $G_W < 1.16$ for $H = 10$ and $W < 50$.

The graphical characteristic of the gain of using multifibers G_F is plotted in Figure 10 for the no wavelength conversion scenario like a comparison of using multifiber network path $F = 10$ instead of the single-fiber network path $F = 1$. The gain is extremely high for $W = 1$, for example, $G \approx 4000$ for $H = 10$, because the probability that there is no wavelength continuous lightpath is too high for no wavelength conversion single-fiber network paths in contrast to no wavelength conversion multifiber paths $F = 10$. The gain G_F decreases dramatically as the number of wavelengths increases until about $W < 10$. Then it decreases very slowly and almost linearly. The convergence of the gain $G_F = 1$ is extremely slow for $W \rightarrow \infty$. From the figure, it can be seen that the gain is still high, for example, $G_F \approx 8$ for $W = 20$ and $H = 10$.

Figure 11 is plotted for the comparison of full wavelength conversion multifiber network paths $F = 10$ and no wavelength conversion single-fiber network paths $F = 1$. It can be observed that the curves are very similar to the previous case although the multifiber network path enables full wavelength conversion. The gain G is for $F \leq W$ quite high, for example,

TABLE 3: The gain of performance, $W = 5$, $H = 10$, and $P_b = 10^{-3}$.

$F = 1$	No	1					
	Lim	4.0989	1				
	Full	5.5591	1.3562	1			
$F = 10$	No	24.5736	5.9951	4.4204	1		
	Lim	28.2967	6.9034	5.0902	1.1515	1	
	Full	29.1722	7.1170	5.2476	1.1871	1.0309	1
$H = 10,$ $W = 5,$ $P_b = 10^{-3}$		No	Lim	Full	No	Lim	Full
			$F = 1$			$F = 10$	

TABLE 4: The gain of performance, $W = 20$, $H = 10$, $P_b = 10^{-3}$.

$F = 1$	No	1					
	Lim	3.0222	1				
	Full	5.4484	1.8028	1			
$F = 10$	No	6.9604	2.3031	1.2775	1		
	Lim	7.7744	2.5724	1.4269	1.1169	1	
	Full	8.2463	2.7286	1.5135	1.1848	1.0607	1
$H = 10,$ $W = 20,$ $P_b = 10^{-3}$		No	Lim	Full	No	Lim	Full
			$F = 1$			$F = 10$

FIGURE 10: The gain of performance $G_W = f(W)$, $P_b = 10^{-3}$, and $F = 10$ No/ $F = 1$ no. FIGURE 11: The gain of performance $G = f(W)$, $P_b = 10^{-3}$, and $F = 10$ Full/ $F = 1$ no.

$G \approx 9$ for $W = 20$ and $H = 10$. However, the difference in gain is not very significant in comparison to previous case.

Note that the performance gain compares the wavelength utilization between any two different optical networks. Generally, there are 15 possibilities. Unfortunately, the detailed explanation and graphical presentation of all possibilities are beyond the scope of this paper. However, this research is the subject of a PhD Thesis [6] which is recommended to be

read. The numerical results of all possibilities are summarized in Table 3 for $W = 5$, $H = 10$, and $P_b = 10^{-3}$; and in Table 4 for $W = 20$, $H = 10$, and $P_b = 10^{-3}$ [6].

The performance gain of using single-fiber network paths with small conversion degree $k = 3$ (limited wavelength conversion) instead of single-fiber network paths with no wavelength conversion is rather high. Hence the implementation of the limited wavelength conversion into

single-fiber network paths is profitable. For full wavelength conversion scenarios the gain is even higher.

The gain of using multifiber network paths is also really high. Hence the application of multifiber network paths is really significant. Moreover, the cable cost of multifiber cables is still decreasing. The difference between using limited or full wavelength conversion multifiber network paths instead of no wavelength multifiber network paths is negligible. Hence there is no reason to replace single-fiber network paths by limited or full wavelength conversion multifiber network paths, but only with no wavelength conversion multifiber network paths. In this case, no wavelength conversion multifiber network paths seem to be the optimal solution in terms of network performance and cost.

The results of comparison of different optical path scenarios in term of the gain are briefly summarized as follows:

- (i) the gain of wavelength conversion G_W is rather high for single-fiber network paths;
- (ii) the gain of wavelength conversion G_W is quite small for multifiber network paths;
- (iii) the gain of using multiple fibers G_F is still quite high depend on the range of wavelength conversion of single-fiber network paths.

5. CONCLUSION

In this paper, a new theoretical model for analyzing blocking performance in both single-fiber and multifiber optical network paths with no, limited, or full wavelength conversion is proposed. The method of computing overall blocking probability of any arbitrary WDM networks using the proposed model is also presented. The numerical results of the model are also presented. Taking into consideration both the wavelength utilization and the blocking probability determined by this model, the optimal network could be designed. The simplicity of the model enables detailed analysis of any optical network and it can be also used to solve the optimal wavelength placement converter problem.

The model is general and, moreover, it shows that a no wavelength conversion multifiber network path with F fibers per link and with W wavelengths on each fiber yields same performance as a limited wavelength conversion of degree F single-fiber network path with $F \cdot W$ wavelengths per fiber on each link.

Thanks to the proposed model and gain of performance, any two different optical network path scenarios can be compared in terms of their performance or blocking probability. The results, which appear interesting, are presented in the paper. The most important conclusions from this paper are that a no wavelength conversion multifiber network path has similar blocking performance to a limited or full wavelength conversion single-fiber network path, the gain of wavelength conversion G_W is rather high for single-fiber in contrast to multifiber network path and the gain of using multiple fibers G_F is still quite high. Most of the current optical networks are built on multiple fibers. Multifiber WDM networks without wavelength conversion is not only a feasible, but also a desirable choice using current technologies. Moreover, the multi-

fiber networks may also offer a cost advantage depending on the relative cost of optical components.

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