# 다수의 광섬유와 산재한 제한 영역 파장 변환기로 구성된 파장분할다중화 광통신망의 성능 분석 모형

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# Analytical Model for Multi-Fiber WDM Networks with Sparse and Limited Wavelength Conversion

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요 약

본 논문에서는 다수의 광섬유로 이루어진 광링크와 산재하여 있는 제한 영역 파장변환 능력을 가진 노드들로 구성된 광통신망의 불통확률을 정확하게 계산할 수 있는 새로운 성능분석 모형을 제안한다. 제안하는 성능분석 모형은 다수의 광섬유로 이루어진 광링크 상에서 사용 가능한 파장들의 분포와 제한 영역 파장변환 이후의 사용 가능한 파장들의 분포, 그리고 다수의 광링크가 연결된 광경로에서의 불통 확률을 계산하기 위한 재귀적 공식을 도출함을 특징으로 한다. NSFNET 망에서 수행한 시뮬레이션 결과를 통해 제안하는 성능분석 모형이 광통신망의 불통확률을 정확히 예측함을 보인다. 또한, 파장 연속성 제약이 없는 경우의 이상적인 불통확률에 근접하는 성능을 얻기 위해서 소수의 제한영역 파장변환 노드와 소수의 광섬유만으로 구성된 광링크를 포설하는 것으로 충분함을 보인다.

**Key Words :** blocking performance, wavelength routing, multi-fiber WDM networks, sparse and limited wavelength conversion.

ABSTRACT

In this paper, we present a new analytical model for estimating the blocking performance of multi-fiber WDM networks with sparse and limited wavelength conversion (SLWC). The proposed model is a reduced-load approximation model that can obtain accurate estimates of blocking probability of such networks. Our model employs three new recurrence formulae to obtain the free wavelength distribution on a multi-fiber link, the free wavelength distribution after limited-range wavelength conversion, and the end-to-end blocking probability of a multi-hop path, respectively. From the numerical results on the NSFNET, we demonstrate that the blocking performance of two-fiber NSFNET with three wavelength-convertible nodes, each of which translates an input wavelength to its adjacent output wavelengths, closely approximates the blocking performance of full wavelength conversion.

## I. Introduction

For the last two decades, wavelength-division multiplexing (WDM) technology employing wavelength routing has been considered as the most viable solution for wide-area networks. In such networks,

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it is widely known that the capability of converting an input optical channel to a different output optical channel can significantly improve the blocking performance. To aim this, two approaches have been considered in the literature: to employ wavelength convertible devices on the node[1]-[6] and to deploy multiple fibers per link[7][8].

Researchers have extensively investigated the role of *wavelength conversion* in the blocking performance of such networks[1][2]. Since it is very difficult and expensive to implement all-optical full-range wavelength converters, most of the recent research work has focused on (single-fiber) networks with sparse and/or limited wavelength conversion[3][4][6]. However, the model in [3] is restricted to the regular topology, while the model in [4] does not reflect the restriction of wavelength conversion capability near both ends of wavelength indexes, due to the assumption that the wavelength conversion is circularly symmetric. As shown in [6], the model tends to underestimate the blocking probability for low traffic loads, while it overestimates the blocking probability for high traffic loads.

The contemporary practice of deploying a bunch of fibers has led many researchers to study the blocking performance of multi-fiber WDM networks[7][8]. In [7], the authors proposed the multi-fiber link-load correlation (MLLC) model that can account for the load correlation between two adjacent links. The research in [8] proposed a simple model for calculating the free wavelength distribution of a multi-fiber link. However, the previous models consider only the networks without wavelength conversion, and thus the benefit of wavelength conversion in such networks has not been investigated before.

Those limitations of the previous work motivate us to introduce a new analytical model for estimating the blocking performance of multi-fiber WDM networks with *sparse and limited wavelength conversion (SLWC)*. In this paper, we believe that both approaches can be used for optimizing the blocking performance in a cooperative manner. To provide the analytical grounds of this belief, we present a new analytical model based on the *reduced-load approximation analysis* that can accurately estimate the blocking probabilities with moderate computational complexity. Our model is the first analytical model that can be applicable to the networks with arbitrary topology, with WDM links consisting of multiple optical fibers, and with a fraction of nodes, named the *wavelength convertible nodes (WCNs)*, that have the capability of translating an input wavelength to a subset of output wavelengths. Before we proceed, we first summarize the notations used for our analysis in section II. Section III presents a set of recurrence formulae to obtain 1) the free wavelength distribution on a multi-fiber link; 2) the free wavelength distribution after limited-range wavelength conversion; and 3) the end-to-end blocking probability of a multi-hop path. Through extensive simulations on the NSFNET, we will verify the accuracy of the proposed model in section IV. From the results, it is also shown that two-fiber NSFNET with three WCNs translating to only adjacent wavelengths give a blocking performance close to that of full wavelength conversion. Finally, we conclude this paper in section V.

## Ⅱ. Network Model and Definitions

In this section, we define the notations that are used for our analysis throughout this paper:

1) The network has $N$ nodes and $L$ links.

2) Each link consists of $F$ fibers, and each fiber has $W$ wavelengths. $(0 \le f < F, 0 \le w < W)$

3) The network has $M$ WCNs. A WCN with *conversion degree* $d$ $(0 \le d \le W)$ converts input wavelength $i$ to the set of output wavelengths in $[\max(i-d, 0), \min(i+d, W-1)]$.

4) Calls are routed on the fixed shortest path $r$ of its source-destination pair. Here, path $r$ defines a set of $h$ links, $r = \{1, 2, \cdots, h\}$, and segment $r_{i \to j}$ represents the consecutive links from link $i$ to link $j$, where $r_{i \to j} = \{i, i+1, \cdots, j-1, j\}$ and $1 \le i \le j \le h$.

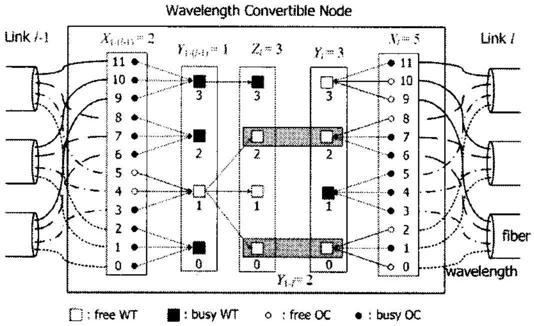


Fig. 1. Conceptual view of wavelength routing between link $l$ and link $(l-1)$ of path $r$.

5) A call request arrives on path $r$ according to the independent Poisson process with rate $\alpha_r$, and has independent holding time following the exponential distribution with unit mean.

6) Traffic load of a link is independent of that of all other links.

7) Wavelength occupancy on fibers and links are independent of one another.

8) A wavelength is randomly selected from the set of available wavelengths on path $r$.

9) The blocked call is immediately discarded from the network.

Fig. 1 shows an example of segment $r_{(l-1)\to l}$ on path $r$, when $F=3$ and $W=4$. Throughout this paper, we refer to a wavelength of a fiber on a link as an *optical channel (OC)*, and the set of $F$ OCs centered at wavelength $w$ as a *wavelength trunk (WT)* on $w$. In Fig. 1, $C\ (=W\times F)$ OCs are first arranged in an ascending order of their WT indexes, and within a WT, in an ascending order of fiber indexes, i.e., OC $wF+f$ stands for the OC centered at wavelength $w$ of fiber $f$. WT $w$ is said to be *free* on link $l$, if wavelength $w$ is free on at least one of the fibers on link $l$; WT $w$ is said to be *busy* on link $l$, otherwise. In Fig. 1, we represent the mapping between free wavelengths by solid lines; Otherwise, the mapping is represented by dotted lines.

Similarly, WT $w$ is free on path $r$ if WT $w$ is *free* on all of the links constituting path $r$; WT $w$ is *busy* on path $r$, otherwise.

Based on the notations, we define several random variables shown in Fig. 1:

1) $X_l$ denotes the number of free OCs on link $l$, where $P_l(m)=\Pr(X_l=m)$.

2) $Y_l$ denotes the number of free WTs on link $l$, where $Q_l(j)=\Pr(Y_l=j)$.

3) $Y_{i\to j}$ denotes the number of free WTs on segment $r_{i\to j}$, where $S_l^-(x)=\Pr(Y_{1\to l}=x)$ and $S_l^+(y)=\Pr(Y_{l\to h}=y)$.

4) $Z_l$ denotes the number of free WTs after wavelength conversion at the $l$-th node of path $r$ where its conversion degree is $d$ and $T_l(i|f)=\Pr(Z_l=i|Y_{1\to(l-1)}=f)$.

Based on the random variables, we also define the (conditional) path-blocking probabilities as follows:

$$\begin{aligned} B_r &= \Pr(Y_{1\to h}=0) \\ B_{r|X_l=m} &= \Pr(Y_{1\to h}=0|X_l=m), \\ B_{r|Y_l=j} &= \Pr(Y_{1\to h}=0|Y_l=j). \end{aligned} \tag{1}$$

Finally, the network-wide blocking probability is given by

$$\overline{B}=\frac{\sum_{\forall r}\alpha_r B_r}{\sum_{\forall r}\alpha_r}. \tag{2}$$

## Ⅲ. Reduced-Load Approximation Analysis

The proposed model consists of a set of equations whose equilibrium fixed points can be solved by repeated substitution[1][4]. At each iteration, we first fix the path-blocking probabilities $B_{r|X_l=m}$ and $B_{r|Y_l=j}$ to get $\alpha_l(m)$, the reduced offered load on link $l$ when $X_l=m$. Then, we fix $\alpha_l(m)$ to get the free OC distribution $P_l(m)$ and the free WT distribution $Q_l(j)$. We also calculate $T_l(i|f)$, the conditional probability of having $i$ free WTs after (limited) wavelength conversion given that the number of free wavelengths at the input of wavelength converter is $f$. Finally, we fix $P_l(m)$, $Q_l(j)$, and $T_l(i|f)$ to get $B_{r|X_l=m}$ and $B_{r|Y_l=j}$. In the following subsections, we address the details of each fixed-point analysis model.

### 3.1 Free OC Distribution

The sum of offered loads on link $l$ is contributed by the offered load of each path $\alpha_r(l \in r)$ thinned by blocking on other links which in turn depends on the number of free OCs on link $l$ [1][4]. The total offered load on link $l$ when $X_l = m$ is then obtained by aggregating all contributions of such paths, i.e.,

$$\alpha_l(m) = \sum_{\forall r : l \in r} \alpha_r (1 - B_{r|X_l = m}). \tag{3}$$

Given $\alpha_l(m)$, the number of free OCs on link $l$ can be viewed as a birth-death process shown in Fig. 2. Then, the free OC distribution $P_l(m)$ is obviously given by

$$P_l(m) = \frac{C(C-1)\cdots(C-m+1)}{\alpha_l(1)\cdots\alpha_l(m)} P_l(0), \tag{4}$$

where

$$P_l(0) = \left[1 + \sum_{m=1}^{C} \frac{C\cdots(C-m+1)}{\alpha_l(1)\cdots\alpha_l(m)}\right]^{-1}. \tag{5}$$

By virtue of the random wavelength assignment, we assume that all wavelength channels on a link are equally likely to be free. Under limited wavelength conversion, however, this may not be true due to the limitation of wavelength conversion near both ends of the wavelength indexes. Nevertheless, with this assumption, we can greatly simplify the following two problems by transforming them into the combinatorial problems.

### 3.2 Free WT Distribution

Given $P_l(m)$, probability $Q_l(j)$ can be obtained by

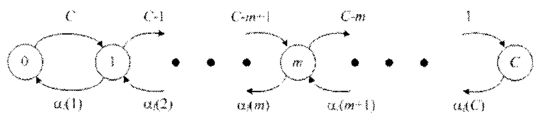


Fig. 2. Markov Chain for the free OC distribution on link $l$.

$$Q_l(j) = \sum_{m=j}^{jF} U_l(j|m) P_l(m), \tag{6}$$

where $U_l(j|m) = \Pr(Y_l = j | X_l = m)$. In this section, we provide a recurrence formula to obtain conditional probability $U_l(j|m)$, where an example, $U_l(2|3)$, is represented by left-arrowed lines in Fig. 1.

Let $\boldsymbol{X}_l$ be the set of $m$ free OCs on link $l$, where $X_l = |\boldsymbol{X}_l|$ and $\boldsymbol{X}_l = \{x_{l,1}, x_{l,2}, \cdots, x_{l,m}\}$, $(x_{l,1} \le x_{l,2} \le \cdots \le x_{l,m})$. For each element $x_{l,k} \in \boldsymbol{X}_l$, the corresponding WT index, $y_{l,k}$, is defined as

$$y_{l,k} = \left\lfloor \frac{x_{l,k}}{F} \right\rfloor, \tag{7}$$

as shown in Fig. 1. Define $\boldsymbol{Y}_l$ as the set of free WTs corresponding to set $\boldsymbol{X}_l$, where $\left\lceil \frac{m}{F} \right\rceil \le Y_l = |\boldsymbol{Y}_l| \le \min(m, W)$.

There are $\binom{C}{m}$ different ways to distribute $m$ free OCs over $C$ different OCs. Let $\psi_U(C,m,j)$ be the number of ways to distribute $m$ free OCs over $C$ different OCs, such that $Y_l = j$. Then, we have

$$U_l(j|m) = \frac{\psi_U(C,m,j)}{\binom{C}{m}}. \tag{8}$$

We can express $\psi_U(C,m,j)$ by conditioning the position of the free OC with the largest OC index. Let us define $\psi_C(a,b,c)$ as the number of *conditional* ways to distribute $b$ free OCs over $a$ different OCs in $[0, a-1]$ such that $c$ WTs are free in $[0, \lfloor a/F \rfloor)$, *given that* the $(b+1)$-th free OC is placed at OC $a$, we can express $\psi_U(C,m,j)$ in terms of $\psi_C(a,b,c)$,

$$\psi_U(C,m,j) = \sum_{w=m-1}^{C-1} \psi_C(w, m-1, j-1). \tag{9}$$

Now, we derive the recurrence relation of $\psi_C(a,b,c)$ by conditioning on the position of the free input OC that is placed at the largest OC index. Let us denote two largest free OC indices by $a$ and $e$, where $e < a$. Note that, if $a$ and $e$ are within the same WT, i.e. $y_{l,a} = y_{l,e}$, the number of free WTs in $[0, \lfloor a/F \rfloor)$ is the same as that in $[0, \lfloor e/F \rfloor)$; Otherwise, $y_{l,e}$ is less than $y_{l,a}$ by 1, i.e.,

$$\psi_C(a,b,c) = \sum_{e=\lfloor \frac{a}{F} \rfloor F}^{a-1} \psi_C(e,b-1,c) + \sum_{e=b-1}^{\lfloor \frac{a}{F} \rfloor F-1} \psi_C(e,b-1,c-1). \quad (10)$$

Finally, the starting point of the recurrence is obtained as follows:

$$\psi_C(a,0,c) = \begin{cases} 1, & \text{if } c = 0; \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

### 3.3 Limited Wavelength Conversion

Now, we provide another recurrence formula to get $T_l(i|f)$, where an example of $T_l(3|1)$ with conversion degree $d=1$ is represented by right-arrowed lines in Fig. 1. Let $Y_{1\to(l-1)}$ be the set of $f$ free WTs at segment $r_{1\to(l-1)}$, where $Y_{1\to(l-1)} = \{y_{1\to(l-1),1}, \cdots, y_{1\to(l-1),f}\}$. Each free input WT $y_{1\to(l-1),k} \in Y_{1\to(l-1)}$ can be converted up to $(2d+1)$ output WTs depending on its wavelength index. Let $z_{l,k}$ be the set of output WTs that input WT $y_{1\to(l-1),k}$ is converted to, then we can partition $z_{l,k}$ into three disjoint subsets:

$$z_{l,k}^- = \{z | \max(y_{1\to(l-1),k} - d, 0) \le z < y_{1\to(l-1),k}\},$$
$$z_{l,k}^0 = \{y_{1\to(l-1),k}\}, \text{ and}$$
$$z_{l,k}^+ = \{z | y_{1\to(l-1),k} < z \le \min(y_{1\to(l-1),k} + d, W-1)\}.$$

Define $Z_l$ as the set of output WTs to which set $Y_{1\to(l-1)}$ is converted. Then, we have $Z_l = \{z_{l,1}\} \cup \cdots \cup \{z_{l,f}\}$, where $Z_l = |Z_l|$ and $\min(f+d, W) \le Z_l \le \min((2d+1)f, W)$.

Defining $\phi_U(W,f,i)$ as the number of ways to distribute $f$ free input WTs over $W$ different WTs such that $Z_l = i$, conditional probability $T_l(i|f)$ can be similarly obtained by

$$T_l(i|f) = \frac{\phi_U(W,f,i)}{\binom{W}{f}}. \quad (12)$$

Let $w = y_{1\to(l-1),f}$ $(f-1 \le w \le W-1)$, where $y_{1\to(l-1),1} \le y_{1\to(l-1),2} \le \cdots \le y_{1\to(l-1),f}$. We also define $\phi_C(a,b,c)$ be the number of *conditional* ways to distribute $b$ free input WTs over $a$ different WTs in $[0, a-1]$ such that $c$ output WTs are free in $[0, a-1]$, *given that* the $(b+1)$-th free input WT is placed at WT $a$. Then, we can express $\phi_U(W,f,i)$ in terms of $\phi_C(a,b,c)$,

$$\phi_U(W,f,i) = \sum_{w=f-1}^{W-1} \phi_C(w, f-1, u), \quad (13)$$

where $u = i - \min(W-1-w, d) - 1$.

In obtaining Eq. (13), we used the fact that, by placing input WT $y_{1\to(l-1),f}$ at $w$, the number of free output WTs in $[0, w-1]$ is $i - |z_{l,f}^0| - |z_{l,f}^+|$, where $|z_{l,f}^0| = 1$ and $|z_{l,f}^+| = \min(W-1-w, d)$. Finally, we can also obtain the recurrence relation of $\phi_C(a,b,c)$ in a similar manner, i.e.,

$$\phi_C(a,b,c) = \sum_{e=b-1}^{a-1} \phi_C(e, b-1, v), \quad (14)$$

where $v = c - \min(a-e-1, 2d) - 1$ and the initial condition is given as follows:

$$\phi_C(a,0,c) = \begin{cases} 1, & \text{if } \min(a,d) = c; \\ 0, & \text{otherwise.} \end{cases} \quad (15)$$

### 3.4 Path-Blocking Probability

To obtain the recursive formula of probability $S_l^-(n)$, we use the fact that the number of free WTs on the $l$-hop segment is independent of the number of free WTs on link $(l-1)$ when the number of free WTs on the path consisting of first $(l-1)$-hop segment is given, i.e.,

$$S_l^-(n) = \sum_{f=0}^{W} S_{l-1}^-(f) \sum_{i=LB(f)}^{UB(f)} T_l(i|f) \sum_{j=n}^{W} Q_l(j) R(n|i,j), \quad (16)$$

where

$$LB(f) = \begin{cases} 0, & \text{if } f = 0; \\ \min(f + d,\ W), & \text{otherwise}, \end{cases}$$
$$UB(f) = \begin{cases} 0, & \text{if } f = 0; \\ \min((2d+1)f,\ W), & \text{otherwise}. \end{cases}$$

From [1]-[8], conditional probability $R(n|i,j) = \Pr(Y_{1\to l} = n | Z_{l-1} = i,\ Y_l = j)$ can be expressed by

$$R(n|i,j) = \binom{i}{n}\binom{W-i}{j-n} \Big/ \binom{W}{j}. \qquad (17)$$

An example of $R(2|3,2)$ is represented by shaded regions in Fig. 1. The initial condition of the recursion $S_l^-(n)$ is obtained by

$$S_1^-(n) = \sum_{m=n}^{F_1 n} P_1(m)\, U_1(n|m). \qquad (18)$$

Recall from Eq. (3) that we need to calculate $B_{r|X_l=m}$ in order to get the state-dependent arrival rates $\alpha_l(m)$. By definition, we can represent probability $B_{r|X_l=m}$ in terms of $U_l(j|m)$ and $B_{r|Y_l=j}$,

$$B_{r|X_l=m} = \sum_{j=\lceil \frac{m}{F} \rceil}^{\min(m,\,W)} U_l(j|m)\, B_{r|Y_l=j}. \qquad (19)$$

To calculate $B_{r|Y_l=j}$, we decompose path $r$ into three independent segments: segment $r_{1\to(l-1)}$, link $l$, and segment $r_{(l+1)\to h}$. Then, we finally have

$$B_{r|Y_l=j} = \sum_{x=0}^{W} V_{l-1}^-(x) \sum_{y=0}^{W} V_{l+1}^+(y) \sum_{z=\max(0,\,x+y-W)}^{\min(x,\,y)} R(z|x,y)\, R(0|z,j), \qquad (20)$$

where

$$V_{l-1}^-(x) = \sum_{f=0}^{W} S_{l-1}^-(f) \sum_{x=LB(f)}^{UB(f)} T_l(x|f), \qquad (21)$$
$$V_{l+1}^+(y) = \sum_{g=0}^{W} S_{l+1}^+(g) \sum_{y=LB(g)}^{UB(g)} T_{l+1}(y|g).$$

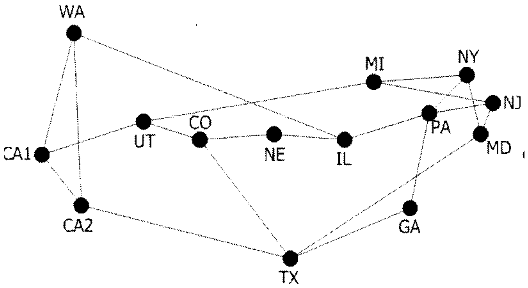


Fig. 3. The NSFNET topology

## Ⅳ. Numerical Results

This section validates the accuracy of the analytical model under different placements of WCNs and under different values of conversion degree. In all experiments, we assume that uniform traffic is offered to the NSFNET consisting of 14 nodes and 21 bi-directional links as shown in Fig. 3.

Fig. 4 shows the network-wide blocking probability against network load for different number of fibers when $C = F \times W = 16$. It is observed that the analytical model slightly overestimates the network-wide blocking probability when $F = 1$, while it closely approximates the blocking probabilities obtained from simulation when $F \geq 2$. This is because our model is basically an independence model, and therefore it

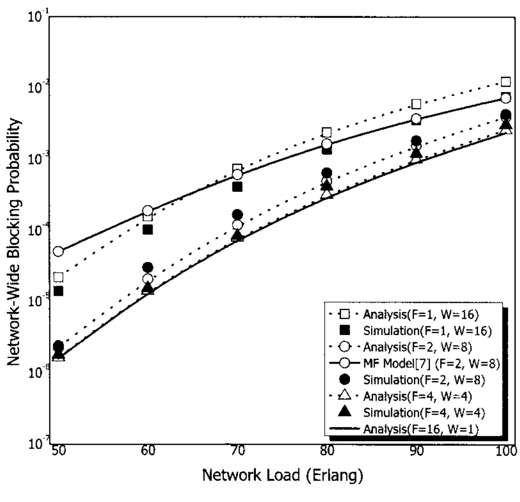


Fig. 4. Blocking probability vs. network load for different number of optical fibers per link.

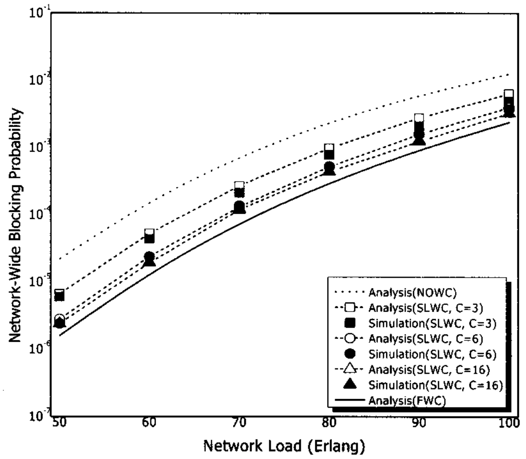


Fig. 5. Blocking probability vs. network load for different number of WCNs, when $F=1$, $W=16$, and $d=1$.

does not account for the occupied-wavelength-index correlation between two adjacent links that is most significant when $F=1$[6]. However, the proposed model can still give much better accuracy than the existing model[8] in the experiment with $F=2$. It is also observed that when $F\geq 4$, the blocking performance of multi-fiber WDM networks is indistinguishable from that of full wavelength conversion, indicating that multi-fiber WDM networks without wavelength conversion can be a viable solution for better blocking performance under current device technology.

Fig. 5. compares the network-wide blocking probabilities of the analytical model with those from simulation for different number of WCNs, when $F=1$, $W=16$ and $d=1$. For SLWC, it is assumed that wavelength converters are placed at nodes *UT, TX, PA* when $M=3$, and at nodes *UT, CO, TX, IL, MI, PA* when $M=6$. The analytical results for two extreme cases of SLWC, i.e., full/no wavelength conversion $d=0/W$, are also plotted in Fig. 5. It is shown that the proposed analysis closely matches with simulation results under different combinations of converter placements. It is also observed that, as the number of WCNs $M$ increases, the blocking probability of SLWC asymptotically approximates that of full wavelength conversion.

Fig. 6. plots the network-wide blocking probabilities against network load for different values of conversion degree, when $F=1$ and $W=16$. The analytical results are also in good agreement with simulation results. We found an interesting fact that increasing the conversion degree does not lead to a significant improvement in blocking probability even when the WCNs are sparsely located, e.g. $M=3$. This indicates that it is more effective to increase the number of WCNs than to increase the conversion degree of wavelength converters.

Fig. 7. shows the network-wide blocking probability against network load for different

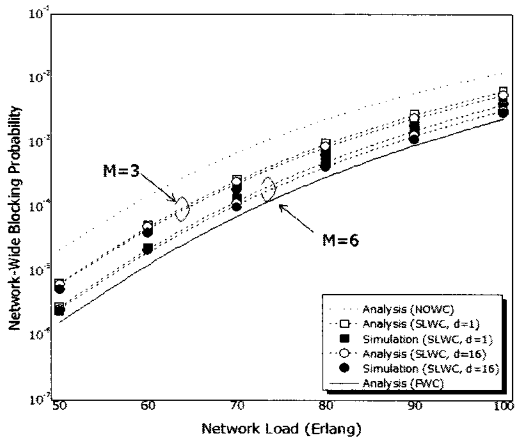


Fig. 6. Blocking probability vs. network load for different values of conversion degree, when $F=1$, and $W=16$.

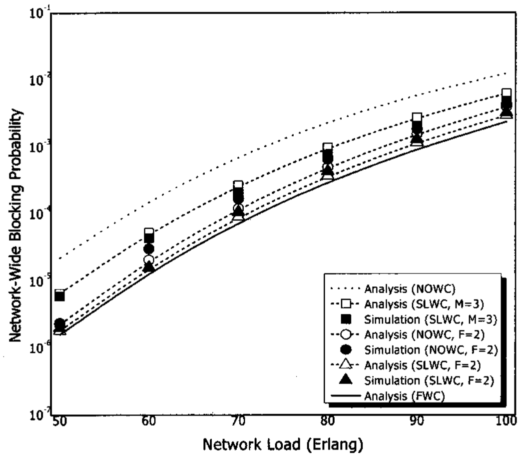


Fig. 7. Blocking probability vs. network load for different combinations of multi-fiber links and SLWCs, when $d=1$ and $M=3$.

combinations of multi-fiber links and sparse-limited wavelength conversions. For SLWC, it is assumed that wavelength converters with $d=1$ are placed at the WCNs ($M=3$). From the figure, it is demonstrated that the proposed analysis closely matches with simulation results under various fiber-converter configurations. It is also reported that the blocking performance of two-fiber NSFNET with three WCNs is almost equal to that of full wavelength conversion.

## V. Conclusion

In this paper, we investigated the problem of computing the blocking probability of multi-fiber WDM networks with sparse and limited wavelength conversion. We presented a new analytical model that is based on the reduced-load approximation analysis. We also derived recurrence formulae to obtain the free wavelength distribution on multi-fiber links, to calculate the free wavelength distribution after limited wavelength conversion, and the end-to-end blocking probability of a multi-hop path. From the numerical results, we verified the accuracy of our model. We also show that the blocking performance of multi-fiber WDM networks with SLWC, consisting of small fraction of WCNs and of small number of optical fibers per link, closely approximates that with full wavelength conversion.

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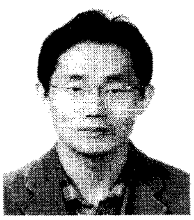

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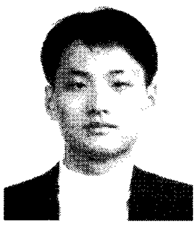

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