Analysis of Blocking Probability for Distributed Lightpath Establishment in WDM Optical Networks

Kejie Lu, *Member, IEEE*, Gaoxi Xiao, *Member, IEEE*, and Imrich Chlamtac, *Fellow, IEEE*

***Abstract*—In this paper, we analyze the blocking probability of distributed lightpath establishment in wavelength-routed WDM networks by studying the two basic methods: destination-initiated reservation (DIR) and source-initiated reservation (SIR). We discuss three basic types of connection blocking: 1) blocking due to insufficient network capacity; 2) blocking due to outdated information; and 3) blocking due to over-reservation. It is shown that the proposed models are highly accurate for both the DIR and the SIR methods, in both the regular and irregular network topologies, under the whole range of traffic loads.**

***Index Terms*—Analytical model, blocking probability, distributed, lightpath establishment, wavelength-routed networks.**

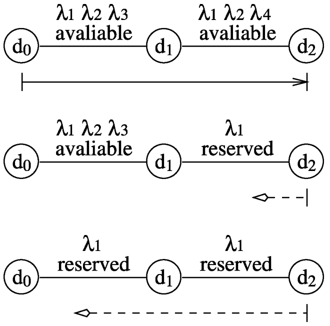

Fig. 1. Example of the DIR method.

I. Introduction

In a WDM network, end-to-end all-optical connections, or lightpaths [1], are established between source-destination node pairs to provide transparent data communication and eliminate the cost and bottlenecks of electronic processing at intermediate nodes. Lightpath-based WDM networks are generally referred to as *wavelength-routed* optical networks. In a wavelength-routed optical network, connection requests for establishing lightpaths arrive at random and after a given holding time, the connections are terminated and the lightpaths are removed from the network. A lightpath establishment protocol is responsible for finding a route and a wavelength for establishing the connection.

Dynamic connection requests in WDM networks can be handled in a centralized or distributed way. In a *centralized* scheme, where information is available at a single location, lightpath may be established more efficiently, as long as optical networks remain relatively small and the traffic is not bursty in nature. To deal with the growth of optical networks and the need for a dynamic allocation of lightpaths, *distributed* schemes have been proposed and are being standardized in the framework of GMPLS [2].

Distributed control schemes can be based on periodical information flooding in the network [3], [4], or based on carefully designed information exchange between neighborhood nodes [5]–[8]. However, in all schemes, the major challenge remains the same: *updated, "current" global information* about wavelength availability cannot be guaranteed at any particular place and time in the distributed system. This will occur since network nodes send out update messages of changed link status only periodically, and secondly, due to propagation delays, the received information is outdated upon arrival. This challenge is inherent to all the distributed schemes. In the cases where traffic is highly static and the average duration of each connection is long, this challenge is not a big concern. However, with the developments of optical Internet, we may soon have to support more and more bursty traffic loads. For example, in wavelength-routed optical burst switched (WROBS) networks [9], it is expected that the connection requests will arrive at a very high speed while the average duration of each connection is only several dozens or hundreds milliseconds. To efficiently support such kinds of bursty traffic, the effects of this challenge have to be thoroughly investigated and fully understood. In this paper, we consider the simplest, most basic cases, the *destination-initiated reservation* (DIR) method and the *source-initiated reservation* (SIR) method [5].

In the DIR method, a control message is forwarded from the source to the destination collecting on the way the wavelength availability information along the path. Based on this information, the destination node will select an available wavelength (if such is available along the path) and send a *reservation request* back to the source node to reserve the selected wavelength. Fig. 1 shows an example of the DIR method. In the SIR method, a *reservation request* control message is sent from the source to the destination, reserving one or more wavelengths along the way as it proceeds toward the destination. The destination node will select one of the reserved wavelength channels (if such are available) and send a *confirmation request* back to the source informing it of the selected wavelength and releasing the others.

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K. Lu was with the Center for Advanced Telecommunications Systems and Services (CATSS), University of Texas at Dallas, Richardson, TX 75083 USA. He is now with the Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611 USA (e-mail: lukejie@ieee.org).

G. Xiao is with the Division of Communication Engineering, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: egxxiao@ntu.edu.sg).

I. Chlamtac is with the Center for Advanced Telecommunications Systems and Services (CATSS), University of Texas at Dallas, Richardson, TX 75083 USA (e-mail: chlamtac@utdallas.edu).

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The DIR and the SIR methods could be used in both the fixed routing and the dynamic routing cases. In this paper, unless otherwise specified, we will discuss the fixed routing case.

The key performance metric in the dynamic lightpath establishment schemes is the connection blocking probability. A lightpath connection request will be blocked when a route with sufficient free capacity cannot be found from the source to the destination, and in the case of wavelength continuous lightpaths (without wavelength converters or opto-electronic conversions) if a wavelength cannot be found between source and destination, the connection request will be blocked even if there is free capacity on every hop of the path. This latter constraint is known as the *wavelength continuity constraint* [1]. In this paper, we commonly term these two types of blocking as blocking due to *insufficient network capacity*. In addition to the above, connection blocking may also occur due to having *outdated global information*. As explained earlier, due to delays caused by the need to collect and transmit the link state information and due to propagation delays, when a control message reaches a link in order to reserve a wavelength channel on it, it is possible that the capacity that was available when the state information of the link was collected, has in the meantime been reserved by another connection request. We call this type of blocking *outdated information* related. The DIR method is a typical case where both of the two types of blocking would occur.

To reduce this type of blocking or to eliminate the need of collecting wavelength availability information, a commonly-used method is one that reserves multiple free wavelength channels on every hop of the route upon the arrival of a connection request, so that there is a high probability that the same wavelength is reserved along the whole path. However, this would cause the *over-reservation* problem, which means that too much network capacity is reserved for this request, and thus some future connection requests may be blocked due to unavailable wavelengths. The SIR method is a typical case where such type of blocking would occur.

Blocking probability in wavelength-routed optical networks has been studied analytically in a number of previous works [10]–[19]. In [10], an analytical model is proposed where correlation of traffic on subsequent links is taken into consideration. However, aiming at providing an insightful yet simple qualitative analysis, it sacrifices the numerical accuracy by making the assumption that the utilization of a wavelength on each link is of a fixed value. In [11], the *reduced load approximation* approach [12] with the *state-dependent arrival model* [13] is used in blocking analysis. This model has been shown to be quite accurate for small networks but has a computational complexity growing exponentially with the number of hops. In addition, it is based on the assumption that the set of available wavelengths on adjacent links are independent. This *link independence assumption* is not valid for networks with sparse topologies. In [14], blocking probability is calculated based on the assumption that the load on the ith hop of a path is only related to the load on the $(i-1)$th hop of it. While this is the first model with an emphasis of considering the *link correlation* in blocking analysis, the proposed model is applicable only to uniform traffic situations and regular network topologies. The work in [15] presents an analytical model that provides similar quality results as to [11], but with a much lower computational complexity. In addition, this work proposes a link correlation model applicable to any network topology. While most studies are based on the link independence assumption or a simplified link correlation model (i.e., link correlation only exists between two adjacent links of a path) in order to keep low computational complexity, an exception is [16], in which a network is decomposed into a set of *path* subsystems. It is claimed that by using this method, higher accuracy can be achieved, though the computational complexity may also be higher.

All of the prior studies have, however, considered only the connection blocking due to insufficient network capacity, assuming in other words, that updated global information is always available. The model presented in [17] was the first to evaluate connection blocking caused by outdated information in distributed schemes.[1] However, the analysis used a link independent model [11]. In order to keep the computation complexity at a reasonable level, some simplifying assumptions had to be made in this work for the analysis of the conflict between different reservation requests, at the expense of accuracy. In this paper, by utilizing and modifying the analytical model proposed in [15], we take into account the special features of the traffic correlation in distributed control schemes. More significantly, for highly bursty traffic cases, a new model is proposed to better reflect the nature of the connection blocking caused by the conflict between different reservation requests. It is also the first time, to the best of our knowledge, that connection blocking due to over-reservation is studied. By studying the two "representative" cases the DIR and the SIR methods, we thus analyze all three different types of connection blocking: 1) blocking due to insufficient network capacity; 2) blocking due to outdated information; and 3) blocking due to over-reservation. It is shown that the analysis is highly accurate for both cases, for both regular and irregular network topologies, under all traffic loads.

The paper is organized as follows. In Section II, we propose an analytical model for the DIR method. We analyze both blocking due to insufficient network capacity and blocking due to outdated information. Section III presents an analytical model for the SIR method which studies the effects of over-reservation. Numerical results are presented in Section IV. Section V concludes the paper.

II. ANALYTICAL MODEL FOR THE DIR METHOD

A. Framework of the Analysis

There are two types of connection blocking when the DIR method is used:

- Blocking in the *forward direction* (i.e., the direction from the source to the destination), due to insufficient network capacity. This type of blocking is also termed *forward blocking*.

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[1] Connection blocking caused by over-reservation was not discussed in that paper. Though the SIR method was discussed, it was assumed that updated global information is always available to the source node at the moment when a reservation request is sent out, and that each reservation request will try to reserve one and only one wavelength channel.

- Blocking in the *backward direction* (i.e., the direction from the destination back to the source), caused by outdated information. This type of blocking is also termed *backward blocking*.

To simplify our analysis, we make the following assumptions. The network is composed of J links connected in an arbitrary topology where each link is composed of C wavelength channels. There are no wavelength converters in the network. Between each pair of source-destination nodes, there is a fixed pre-planned route. When there are multiple free wavelengths along the route, one of them will be *randomly* selected. The connection requests between each pair of source-destination nodes arrive from a Poisson process with an arrival rate λ_R, where R denotes the fixed route between the two nodes.

Between the two end nodes of each link on a route, we call the one closer to the source the *left-hand* node, and the one closer to the destination the *right-hand* node. In this section, we let the *link state* be the state of a link when a connection request reaches the right-hand node of the link.[2] A wavelength channel can be in one of the following three states: 1) free; 2) reserved, yet with no data transmission; and 3) occupied by data transmission. We shall say that in the state 3, the wavelength channel is *busy*; otherwise, it is *idle*.

Let X_j $(j = 1, 2, \cdots, J)$ be the random variable representing the number of idle wavelength channels on link j. Let

$$q_j(m) = \Pr\{X_j = m\}, \quad m = 1, 2, \cdots C \tag{1}$$

be the probability that there are exactly m idle wavelength channels on link j. Following [13] we assume that all X_j's are mutually independent, then the steady-state probability that there are exactly m_j idle wavelength channels on link j $(j = 1, 2, \ldots, J)$ is

$$q(\mathbf{m}) = \prod_{j=1}^{J} q_j(m_j) \tag{2}$$

where

$$\mathbf{m} = (m_1, m_2, \ldots, m_J).$$

We further assume that when there are m idle wavelength channels on link j, the inter-arrival time of connection requests is exponentially distributed with a parameter $\alpha_j(m)$. Following [15] we have

$$q_j(m) = \frac{C(C-1)\ldots(C-m+1)}{\alpha_j(1)\alpha_j(2)\ldots\alpha_j(m)} \cdot q_j(0), \quad m = 1, 2, \ldots, C \tag{3}$$

where

$$q_j(0) = \left[1 + \sum_{m=1}^{C} \frac{C(C-1)\cdots(C-m+1)}{\alpha_j(1)\alpha_j(2)\cdots\alpha_j(m)}\right]^{-1}. \tag{4}$$

Finally, the framework for calculating the steady-state probability $q(\mathbf{m})$ can be summarized as follows.

Calculating Blocking Probability in DIR Method: Framework

1) Initiate $\alpha_j(m), j = 1, 2, \cdots, C$ as follows:

$$\alpha_j(m) = \begin{cases} \sum_{R: j \in R} \lambda_R, & m = 1, 2, \ldots, C \\ 0, & m = 0 \end{cases}. \tag{5}$$

2) Calculate $q(\mathbf{m})$ through (1)–(4).

3) Calculate the blocking probability of R as

$$B_R = B_R^F + \left(1 - B_R^F\right) \times B_R^B = 1 - \left(1 - B_R^F\right) \times \left(1 - B_R^B\right) \tag{6}$$

where B_R^F denotes the forward blocking probability, and B_R^B denotes the backward blocking probability. If for every route R, B_R has been convergent, then stop; otherwise, go to step 4.

4) Calculate $\alpha_j(m), j = 1, 2, \cdots, C$ as follows:

$$\alpha_j(m) = \sum_{R: j \in R} \lambda_{R,j}(m) \triangleq \sum_{R: j \in R} \lambda_R \cdot \left(1 - B_{R|X_j = m}\right) \tag{7}$$

where $\lambda_{R,j}(m)$ denotes the arrival rate of those connection requests for route R which are finally successfully accepted, given that the state of link j is m. Go to step 2.

In step 3, we consider the blocking in both the forward and backward directions as shown in (6). In the following subsections, we will discuss the calculations of B_R^F, B_R^B and $\alpha_j(m)$, respectively.

B. Blocking Due to Insufficient Network Capacity

Connection requests can be blocked in the forward direction due to insufficient network capacity. The main idea is basically the same as that in [11] and [15]: It is based on a link correlation model where the state dependent model is used to describe the link state. However, we take the influence of propagation delay of management messages into consideration. Specifically, due to the propagation delay of reservation request in the *backward* direction, some wavelength channels are reserved for a short period of time before they are actually occupied by data transmission. Such type of reservation could consume some network capacity and make the blocking probability in the *forward* direction slightly higher. This type of influence could be significant when under bursty traffic load. Further improvement in analysis accuracy is achieved by modifying the model proposed in [15] to better analyze the state dependent arrival rate of traffic requests, as will be explained later in Section II-D. Below we present the detailed analysis.

Let $h_{i,R}$ denote the probability that a given set of i wavelength channels are free on route R at the moment when the connection request reaches the destination node. Then from the inclusion-exclusion principle and the assumption of random wavelength assignment, we have

$$B_R^F = 1 - \sum_{i=1}^{C} (-1)^{i+1} \binom{C}{i} h_{i,R}. \tag{8}$$

For a route R, to simplify the description, we denote link j as the jth link of this route and link j' as the $(j-1)$th link of this route (when $j > 1$). Let $Y_{k,j}(t)$ denote the state (busy or idle) of channel k on link j at time t, and t_j denote the propagation

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[2] The reason we make this definition is: Due to the propagation delay, the state of a link can be changed during the period of time when a connection request is moving from the left-hand node to the right-hand node of this link. Therefore, the state information provided by the right-hand node is more updated.

delay on link j. To simplify the analysis, we make the following assumptions [15]:

1) All wavelength channels are statistically identical. This assumption is reasonable since we are using random wavelength assignment.
2) $Y_{k_1,j}(t_j)$ is independent of $Y_{k_2,j'}(0)$ $(k_1 \neq k_2)$ given that $Y_{k_2,j}(t_j)$ or $Y_{k_1,j'}(0)$ is known.
3) $Y_{k,j}(t_j)$ is independent of $Y_{k,j^*}(t)$ $(j^* \neq j, j', \forall t)$ given that $Y_{k,j'}(0)$ is known.

From the assumptions, we have

$$h_{i,R} = \begin{cases} h_{i,1}, & \text{if } L_R = 1 \\ h_{i,1} \cdot \prod_{j=2}^{L_R} h_{i,j|i,j'}(t_j), & \text{otherwise} \end{cases} \tag{9}$$

where L_R denotes the hop length of route R, and $h_{i,j|i,j'}(t_j)$ denotes the conditional probability that a given set of i wavelength channels are free on link j given that t_j time slots ago they were free on link j'. Therefore,

$$\begin{cases} h_{i,1} = g_{i,1} \times f_{i,1} \\ h_{i,j|i,j'}(t_j) = g_{i,j|i,j'}(t_j) \times f_{i,j|i,j'}(t_j) \end{cases} \tag{10}$$

where

- $g_{i,j}$ denotes the steady-state probability that a given set of i wavelength channels are idle on link j.
- $f_{i,j}$ denotes the conditional probability that a given set of i channels are free on link j given that these i channels are idle.
- $g_{i,j|i,j'}(t_j)$ denotes the conditional probability that a given set of i wavelength channels are idle on link j given that t_j time slots ago they were idle on link j'.
- $f_{i,j|i,j'}(t_j)$ denotes the conditional probability that a given set of i wavelength channels are free on link j given that these i channels are idle and t_j time slots ago they were free on link j'.

Below we will discuss the calculations of $g_{i,j}$, $f_{i,j}$, $g_{i,j|i,j'}(t_j)$ and $f_{i,j|i,j'}(t_j)$, respectively.

Calculating $g_{i,j}$ and $g_{i,j|i,j'}(t_j)$: From the definition of $q_j(m)$, we have

$$g_{i,j} = \sum_{m=i}^{C} q_j(m) g_{i,j|X_j=m} \tag{11}$$

where

$$g_{i,j|X_j=m} = \frac{\binom{m}{i}}{\binom{C}{i}} = \prod_{k=1}^{i} \frac{m-k+1}{C-k+1}. \tag{12}$$

Let $F_{k,j}(t_j)$ denote the event that the kth channel on link j is idle at time t_j and $\overline{F_{k,j}}(t_j)$ denote the opposite event. Based on the assumptions before (9), we have

$$\begin{aligned} g_{i,j|i,j'}(t_j) &= \Pr\{F_{i,j}(t_j)|F_{i-1,j}(t_j), \cdots, F_{1,j}(t_j); F_{i,j'}(0)\} \\ &\quad \times \Pr\{F_{i-1,j}(t_j)|F_{i-2,j}(t_j), \cdots, F_{1,j}(t_j); F_{i-1,j'}(0)\} \\ &\quad \times \cdots \times \Pr\{F_{2,j}(t_j)|F_{1,j}(t_j); F_{2,j'}(0)\} \\ &\quad \times \Pr\{F_{1,j}(t_j)|F_{1,j'}(0)\}. \end{aligned} \tag{13}$$

From the link correlation model, we have

$$\Pr\{F_{i,j}(t_j)|F_{i-1,j}(t_j), \ldots, F_{1,j}(t_j); F_{i,j'}(0)\} = \left[1 + \gamma_{j',j}(t_j) \times \left(\frac{1}{\eta_{i,j}} - 1\right)\right]^{-1} \tag{14}$$

where $\eta_{i,j}$ denotes conditional probability that channel i is idle on link j given that all the channel 1 through channel $(i-1)$ are idle, i.e.,

$$\eta_{i,j} = \begin{cases} g_{i,j}, & i = 1 \\ \frac{g_{i,j}}{g_{i-1,j}}, & i > 1 \end{cases} \tag{15}$$

and

$$\gamma_{j',j}(t_j) = \frac{\Pr\{F_{i,j}(t_j)|\overline{F_{i,j'}}(0)\}}{\Pr\{F_{i,j}(t_j)|F_{i,j'}(0)\}} = \frac{\lambda_{j,\overline{j'}}}{\lambda_j}. \tag{16}$$

In (16), λ_j denotes the average rate of the connection requests passing through link j and are finally accepted, and $\lambda_{j,\overline{j'}}$ denotes the average arrival rate of the connection requests passing through link j but not passing through j' and are finally accepted. For more discussions on (14)–(16), please refer to [15].

To summarize, we have

$$g_{i,j|i,j'}(t_j) = \prod_{k=1}^{i} \left[1 + \gamma_{j',j}(t_j) \times \left(\frac{1}{\eta_{k,j}} - 1\right)\right]^{-1}. \tag{17}$$

Calculating $f_{i,j}$ and $f_{i,j|i,j'}(t_j)$: Variable $f_{i,j}$ denotes the probability that a given set of i wavelength channels are free on link j given that these i wavelength channels are idle. This conditional probability measures the influence of propagation delay. From the moment a channel is reserved to the moment it becomes busy, the length of the time interval equals to

$$\tau_R(j) = 2 \times \sum_{l=1}^{j} t_l \tag{18}$$

which means the round-trip propagation delay from the source node of route R to the right-hand node of link j. Therefore, $f_{i,j}$ can be calculated as follows:

$$f_{i,j} = \sum_{m=i}^{C} q_{j|i}(m) \prod_{R:j \in R} \left(1 - \left(1 - e^{-\lambda_R(m)\tau_R(j)}\right) \times \frac{i}{m}\right) \tag{19}$$

where $q_{j|i}(m)$ denotes the probability that m channels are idle on link j given that a specific set of i channels $(i \leq m)$ are idle on this link, i.e.,

$$q_{j|i}(m) = q_j(m) \times \frac{g_{i,j|X_j=m}}{g_{i,j}}. \tag{20}$$

The basic idea for calculating $f_{i,j|i,j'}(t_j)$ is nearly the same as that for calculating $f_{i,j}$. The only difference is: If the reservation request also passes through link j' and at time t the channel on link j is reserved but not busy, then the reservation request must have arrived the right-hand node of link j within the time interval $(t - 2t_j, t)$; otherwise, the same wavelength on link j'

should have been reserved at time $t - t_j$. Therefore, we define that for any route R passing through link j

$$\tau_R(j, j') = \begin{cases} \tau_R(j), & j' \notin R \\ 2 \times t_j, & j' \in R. \end{cases} \tag{21}$$

Then $f_{i,j|i,j'}(t_j)$ can be calculated by using (19) where $\tau_R(j)$ is replaced by $\tau_R(j, j')$.

C. Blocking Due to Outdated Information

Connection blocking could happen in the backward direction due to outdated information. More specifically, such blocking will happen if and only if we have several reservation requests competing for a same wavelength channel. The detailed analysis is as follows.

If $L_R = 1$, obviously $B_R^B = 0$. Therefore we will only consider the case when $L_R > 1$. When a reservation request for route R reaches the right-hand node of a link j ($j < L_R$), it can be blocked if and only if there is an interfering reservation request arrived earlier. In addition, this interfering reservation request must have arrived *after* the connection request for R passed link j. Another observation is that if the reservation request for R gets blocked on link j, then the interfering reservation request cannot have gone through the $(j+1)$th link of route R (denoted as j''); otherwise, the reservation request for route R should have been blocked on link j''. Based on these two observations and the fact that the round-trip propagation delay between the right-hand node of link j and the destination of route R equals to

$$t_R(j) = 2 \times \sum_{l=j+1}^{L_R} t_l \tag{22}$$

we have

$$B_R^B = 1 - \prod_{j=1}^{L_R - 1} w_{j,j''}\left(t_R(j)\right) \tag{23}$$

where $w_{j,j''}(t_R(j))$ denotes the conditional probability that no interfering reservation requests has arrived link j within the past $t_R(j)$ time slots and reserved the same wavelength, given that j'' is not on the route of that interfering reservation request. From this definition, we have

$$w_{j,j''}\left(t_R(j)\right) = 1 - \sum_{m=1}^{C} \frac{q_j(m)}{m} \times \left(1 - e^{(-1) \times \lambda_{j,\overline{j''}}(m) \times t_R(j)}\right) \tag{24}$$

where $\lambda_{j,\overline{j''}}(m)$ denotes the total arrival rate of those connection requests which pass through link j but not link j'' and are finally successfully accepted, given that the state of link j is m. Therefore

$$\lambda_{j,\overline{j''}}(m) = \sum_{R: j \in R, j'' \notin R} \lambda_{R,j}(m). \tag{25}$$

D. State Dependent Arrival Rate

To complete the calculation of the overall connection blocking probability for DIR method, as described in step 4 of the Framework in Section II-A, it remains to obtain the state dependent arrival rate $\alpha_j(m)$. From (7), we see that in order to obtain $\alpha_j(m)$, we need to calculate $B_{R|X_j=m}$.

Similar to (6), we have

$$B_{R|X_j=m} = B_{R|X_j=m}^F + \left(1 - B_{R|X_j=m}^F\right) \times B_{R|X_j=m}^B \tag{26}$$

where $B_{R|X_j=m}^F$ and $B_{R|X_j=m}^B$ are two conditional probabilities that need to be calculated first.

Calculating $B_{R|X_j=m}^F$: $B_{R|X_j=m}^F$ can be calculated as

$$B_{R|X_j=m}^F = 1 - \sum_{i=1}^{C} (-1)^{i+1} \binom{C}{i} h_{i,R|X_j=m} \tag{27}$$

which resembles (8). Variable $h_{i,R|X_j=m}$ denotes the conditional probability that a given set of i channels are free on R at the moment when the connection request reaches its destination, given that m wavelength channels are idle on link j. The main idea of calculating $h_{i,R|X_j=m}$ is to slightly modify (9) and (10) to take the additional condition $X_j = m$ into consideration. In other words, we need to calculate four probabilities: $g_{i,j|X_j=m}$, $g_{i,j|i,j';X_j=m}(t_j)$, $f_{i,j|X_j=m}$, and $f_{i,j|i,j';X_j=m}(t_j)$. Since we already got $g_{i,j|X_j=m}$ in (12), below we will consider the other three probabilities:

$$\begin{cases} g_{i,j|i,j';X_j=m}(t_j) = \prod_{k=1}^{i} \left[1 + \gamma_{j',j}(t_j) \cdot \frac{C-m}{m-k+1}\right]^{-1} \\ f_{i,j|X_j=m} = \prod_{R: j \in R} \left(1 - \left(1 - e^{-\lambda_{R,j}(m)\tau_R(j)}\right) \cdot \frac{i}{m}\right) \\ f_{i,j|i,j';X_j=m}(t_j) = \prod_{R: j \in R} \left(1 - \left(1 - e^{-\lambda_{R,j}(m)\tau_R(j,j')}\right) \cdot \frac{i}{m}\right). \end{cases} \tag{28}$$

Remark: The first equation in (28) is quite similar to (17), with only one slight yet important difference. That is, there is an additional condition that $X_j = m$, which leads to a more accurate correlation model. With this additional condition, we have from the definition in (15) that

$$\eta_{k,j|X_j=m} = \frac{m-k-1}{C-k-1}. \tag{29}$$

Therefore

$$\frac{1}{\eta_{k,j;X_j=m}} - 1 = \frac{C-m}{m-k+1}. \tag{30}$$

As will be shown in Section IV, this slight modification could significantly improve the accuracy of the analytical model, especially when under heavy traffic load.

Calculating $B_{R|X_j=m}^B$: Obviously $B_{R|X_j=m}^B = 0$ when $L_R = 1$. Thus, again, we only consider the case when $L_R > 1$. $B_{R|X_j=m}^B$ can be calculated by using (23) with $w_{j,j''}(t_R(j))$ be replaced by $w_{j,j''|X_j=m}(t_R(j))$ where

$$w_{j,j''|X_j=m}\left(t_R(j)\right) = 1 - \frac{1}{m} \times \left(1 - e^{(-1) \times \lambda_{j,\overline{j''}}(m) \times t_R(j)}\right). \tag{31}$$

E. Computational Complexity

The computational complexity of the analytical model can be analyzed as follows: Let H denote the maximum number of hops in any route in the network, I denote the average number of routes passing through each link, and A denote the average nodal degree of the network. From (11) and (13), we observe that the calculations of all the $g_{i,j}$'s and $g_{i,j|i,j'}(t_j)$'s need $O(JC^2)$ and $O(JC^2A)$ operations, respectively. As to the calculations of $f_{i,j}$'s and $f_{i,j|i,j'}(t_j)$'s on all the links, as we could observe from (19), they require $O(JC^2I)$ and $O(JC^2IA)$ operations, respectively.

To compute the blocking probability of a route, we observe from (8), (9) and (23), (24) that it requires $O(HC)$ operations.

III. ANALYTICAL MODEL FOR THE SIR METHOD

In the SIR method, multiple free wavelength channels are reserved upon the arrival of a connection request, so that there is a high probability that the same wavelength is reserved along the whole path. Consequently, connection blocking can be caused by insufficient network capacity as well as the over-reservation of the wavelength channels.

Within the frame of the SIR method, different variants reserve different number of wavelength channels when a reservation request is forwarded from the source to the destination and release the surplus reserved wavelength channels at different time [5]. For the sake of this case study, we will consider the following specific method:

- For a single-hop route, a free wavelength channel (if any) will be selected and occupied by data transmission without a prior reservation and confirmation.
- For a multi-hop route, all the free wavelength channels on the first hop will be reserved. On each of the following hops, among all the free wavelength channels, only those that are free on *all* the previous hops will be reserved. The only exception is the *last* hop, on which a single free wavelength channel is selected and reserved with no need of a confirmation (if applicable). Meanwhile, a confirmation request will be sent by the node *before* the destination node to reserve the same wavelength on all the previous hops back to the source node.

Fig. 2 shows an example of the above specific SIR method.

To simplify the description, we call a wavelength channel as *nonconfirmed* if it is reserved but not confirmed yet. The basic assumptions of traffic model and network topology we made in Section II-A still hold unless otherwise specified. In addition, we assume that among all the wavelength channels that are reserved along the route, one of them is *randomly* selected and confirmed while the others are released. Beginning with a brief description of the analytical model for the SIR method, we then present the detailed method for analyzing the effects of over-reservation.

A. Analytical Model for the SIR Method: A Brief Description

In the SIR method, connection blocking occurs only in forward direction. Therefore, the blocking probability equals to

$$B_R = B_R^F = 1 - \sum_{i=1}^{C} (-1)^{i+1} \binom{C}{i} h_{i,R} \tag{32}$$

where $h_{i,R}$ denotes the probability that a given set of i wavelength channels are available along the whole route (i.e., have been successfully reserved by the reservation request for route R). The calculation of the $h_{i,R}$ for the SIR method is quite similar to that for the DIR method as shown in (9), with several slight yet important differences. We list these differences as follows:

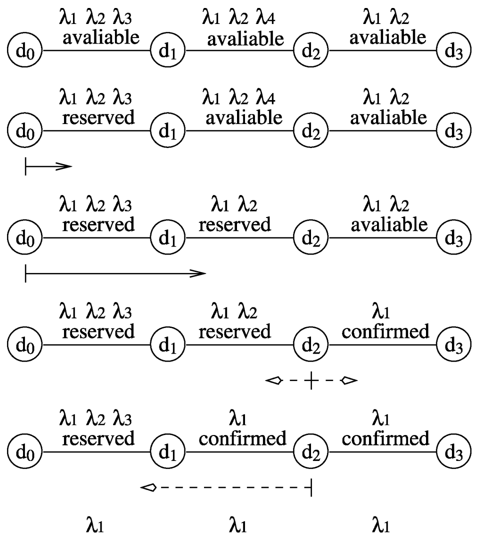

Fig. 2. Example of the specific SIR method.

1) In Section II-A, we define the link state as the state of the link at the moment when the connection request reaches the right-hand node of the link. In the SIR method, however, since all the reservation decisions are made based on the state information provided by the left-hand node of the link, we let the *link state* be the state of a link when a connection request reaches the left-hand node of the link. Due to this difference, the calculation of $h_{i,R}$ in (9) needs to be slightly modified as follows:

$$h_{i,R} = \begin{cases} h_{i,1}, & \text{if } L_R = 1 \\ h_{i,1} \cdot \prod_{j=2}^{L_R} h_{i,j|i,j'}(t_{j'}), & \text{otherwise.} \end{cases} \tag{33}$$

2) In the SIR method, a wavelength channel can be in one of the following *four* states: 1) free; 2) nonconfirmed; 3) confirmed, yet with no data transmission; 4) occupied by data transmission. Similar to that in Section II, we shall say that in the state 4, the wavelength channel is *busy*; otherwise, it is *idle*. Since there is one more state compared to that in the DIR case, the equation (10) is modified as

$$\begin{cases} h_{i,1} = g_{i,1} \times z_{i,1} \times u_{i,1} \\ h_{i,j|i,j'}(t_{j'}) = g_{i,j|i,j'}(t_{j'}) \times z_{i,j|i,j'}(t_{j'}) \times u_{i,j|i,j'}(t_{j'}) \end{cases} \tag{34}$$

where

- $z_{i,1}$ denotes the conditional probability that a given set of i channels are either free or nonconfirmed on the first link of the route given that these channels are idle; and $u_{i,1}$ denotes the conditional probability these i channels are free given that they are either free or nonconfirmed;
- $z_{i,j|i,j'}(t_{j'})$ denotes the conditional probability that a given set of i channels are either free or nonconfirmed on link j given that they are idle and $t_{j'}$ time slots ago they were free on link j'; and $u_{i,j|i,j'}(t_{j'})$ denotes the

conditional probability that these i wavelength channels are free on link j given that they are either free or nonconfirmed and $t_{j'}$ time slots ago they were free on link j'. In (34), the method for calculating $g_{i,j|i,j'}(t_{j'})$ can be seen in (13)–(17). The calculation of $z_{i,1}$ is nearly the same as that for calculating $f_{i,1}$ in (19) except that the length of propagation delay is changed (because the state information is now provided by the left-hand node of the link). Specifically, the $\tau_R(j)$ in (19) is replaced by

$$\tau'_R(j) = 2 \times \sum_{l=1}^{j-1} t_l. \tag{35}$$

Similarly, the calculation of $z_{i,j|i,j'}(t_{j'})$ is nearly the same as that for calculating $f_{i,j|i,j'}(t_{j'})$ except that the $\tau_R(j,j')$ in (21) is replaced by

$$\tau_R(j,j') = \begin{cases} 2 \times \tau'_R(j), & j' \notin R \\ 2 \times t_{j'}, & j' \in R. \end{cases} \tag{36}$$

From the above discussions, we see that the effects of over-reservation are measured by two new variables: $u_{i,j}$ and $u_{i,j|i,j'}(t_{j'})$. We will present the detailed method for calculating them in the next subsection.

B. Analysis of the Effects of Over-Reservation

Calculating $u_{i,j}$: From the definition of $u_{i,j}$, we see that if i channels are either free or nonconfirmed on link j, the probability that they are free equals to the probability that there is no reservation reserving any one of them. To simplify the analysis, we assume that whenever a reservation request reaches the left-hand node of a link, there is at most one interfering reservation request on this link. In other words, all the nonconfirmed wavelength channels on this link, if any, were reserved by a single reservation request arrived earlier. Furthermore, we define the number of wavelength channels a reservation request would *attempt* to reserve on a link as follows:

- On the first link of a route, a reservation request would attempt to reserve all the C wavelength channels.
- On the lth $(l > 1)$ link of a route, the number of wavelength channels that a reservation request would attempt to reserve equals to the number of wavelength channels that this reservation request has successfully reserved on the $(l-1)$th link of the route.

Based on this basic definition, we denote

- $v_{R,j}(n)$ as the steady-state probability that a reservation request for route R attempts to reserve n channels on link j (with no guarantee of how many channels can actually be reserved);
- $v_j(n)$ as the steady-state probability that there is a certain reservation request passing through link j attempting to reserve n channels on this link. For the special case when $n = 0$, $v_j(n)$ denotes the probability that (1) there would be a reservation request passing through link j if it had not been blocked on a certain previous link of its route, or (2) there is no reservation request passing through link j simply because no one is sending such a request.

Therefore, we have

$$v_j(n) = \begin{cases} 1 - \sum_{R:j\in R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) \\ \quad + \sum_{R:j\in R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) v_{R,j}(0), & n = 0 \\ \sum_{R:j\in R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) v_{R,j}(n), & n = 1,2,\ldots,C \end{cases} \tag{37}$$

where $t^*_R(j)$ denotes the duration that a wavelength channel could remain in the nonconfirmed state if it is reserved for route R. This duration equals to the round-trip propagation delay between the left-hand node of this link and the left-hand node of the last link of the route. Therefore

$$t^*_R(j) = \begin{cases} 2 \times \sum_{l=j}^{L_R - 1} t_l, & j < L_R \\ 0, & j = L_R. \end{cases} \tag{38}$$

The method for calculating $v_{R,j}(n)$ will be discussed later.

Finally, we see that if i channels are either free or nonconfirmed on link j, they are free if and only if there is no reservation request attempting to reserve any one of them. Therefore

$$u_{i,j} = \sum_{n=0}^{C-i} v_j(n) \frac{\binom{C-n}{i}}{\binom{C}{i}}. \tag{39}$$

Calculating $u_{i,j|i,j'}(t_{j'})$: The method for calculating $u_{i,j|i,j'}(t_{j'})$ is quite similar to that for calculating $u_{i,1}$. The main difference is that if an interfering reservation request passes through both link j' and link j, then wavelength conflict will happen on link j'. Therefore, by defining $v_{j,\overline{j'}}(n), n = 0,1,\ldots,C$ as the steady-state probability that there is a certain reservation request attempting to reserve n channels on link j given that this reservation request does not pass through link j', we have

$$v_{j,\overline{j'}}(n) = \begin{cases} 1 - \sum_{R:j\in R;j'\notin R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) \\ \quad + \sum_{R:j\in R;j'\notin R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) v_{R,j}(0), & n = 0 \\ \sum_{R:j\in R;j'\notin R} \left(1 - e^{-\lambda_R \cdot t^*_R(j)}\right) v_{R,j}(n), & n = 1,2,\ldots,C. \end{cases} \tag{40}$$

Similar to that in (39), $u_{i,j|i,j'}(t_{j'})$ can be calculated as

$$u_{i,j|i,j'}(t_{j'}) = \sum_{n=0}^{C-i} v_{j,\overline{j'}}(n) \frac{\binom{C-n}{i}}{\binom{C}{i}}. \tag{41}$$

Calculating $v_{R,j}(n)$: $v_{R,j}(n)$ can be calculated iteratively. Specifically, initially we set

$$v_{R,j}(n) = \begin{cases} 1, & n = 1,\ j = L_R \\ 1, & n = C,\ j \neq L_R \\ 0, & \text{otherwise}. \end{cases} \tag{42}$$

Then $h_{i,1}$ and $h_{i,j|i,j'}(t_{j'})$ can be calculated as shown in (33). Iteratively, if link j is not the first hop of route R, we update the value of $v_{R,j}(n)$ as follows:

$$v_{R,j}(n)=\begin{cases} 1-\sum_{k=1}^{C}(-1)^{k+1}\binom{C}{k}h_{k,j,R}, & n=0\\ \binom{C}{n}\cdot\sum_{k=n}^{C}(-1)^{n+k}\binom{C-n}{k-n}h_{k,j,R}, & n=1,2,\ldots,C \end{cases} \tag{43}$$

where $h_{i,j,R}$ denotes the probability that a reservation request for route R attempts to reserve a given set of i wavelength channels on link j $(j>1)$. Thus

$$h_{i,j,R}=\begin{cases} h_{i,1}, & j=2\\ h_{i,1}\times\prod_{l=2}^{j}h_{i,j|i,j'}(t_{j'}), & j\neq 1,2. \end{cases} \tag{44}$$

Once the new $v_{R,j}(n)$ has been calculated, $h_{i,1}$ and $h_{i,j|i,j'}(t_{j'})$ can be updated. The iteration can be repeated until the results converge. Please note that in all the iterations, the value of $v_{R,1}(n)$ remains unchanged.

C. Computational Complexity

As those in Section II-E, we still let H denote the maximum number of hops in any route in the network, I denote the average number of routes passing through each link, and A denote the average nodal degree of the network. We observe that the calculations of all the $g_{i,j}$'s and $g_{i,j|i,j'}(t_j)$'s need $O(JC^2)$ and $O(JC^2A)$ operations, respectively, the same as those in the DIR analytical model. As to the calculations of all the $z_{i,1}$'s and $z_{i,j|i,j'}(t_{j'})$'s, they require $O(JC^2I)$ and $O(JC^2IA)$ operations respectively, the same as those for calculating $f_{i,1}$'s and $f_{i,j|i,j'}(t_{j'})$'s in the DIR analytical model.

Equations (39) and (41) show that calculating all the $u_{i,j}$'s and $u_{i,j|i,j'}(t_{j'})$'s requires $O(JC^2)$ and $O(JC^2A)$ operations, respectively. As to the calculations of all the $v_j(n)$'s (37) and $v_{j,\overline{j'}}(n)$'s (40), they require $O(IJC)$ and $O(IJAC)$ operations, respectively.

For a route R, the calculations of all the $h_{i,j,R}$'s (44) and $v_{R,j}(n)$'s (43) require $O(HC)$ and $O(HC^2)$ operations, respectively. The $h_{i,R}$ is equivalent to the special case of $h_{i,j,R}$ where $j=L_R$ (33), which can then be used to calculate the blocking probability of the route (32).

IV. NUMERICAL RESULTS

To evaluate the accuracy of the proposed analytical models, especially when under highly bursty traffic loads, we compare the analysis results to the simulation results on both the PacNet (shown in Fig. 3 where the numbers next to the links denote the physical length in tens of kilometers) and a 12-node optical ring (where the length of the fiber between every two adjacent nodes is 100 kilometers). In all our simulations, unless otherwise specified, we assume that: 1) each link is composed of two directional fibers of opposite directions with eight wavelength channels per fiber; 2) the connection requests arrive from a Poisson process with exponentially distributed duration; 3) the traffic pattern is uniform, i.e., the average arrival rate of the connection requests between each pair of source-destination nodes is a constant; and 4) the fixed shortest path routing is used between each pair of source-destination nodes. In all the figures for simulation results, we let the traffic load measured in Erlang on the x-axis denote the average traffic load sourced from every node on every wavelength.

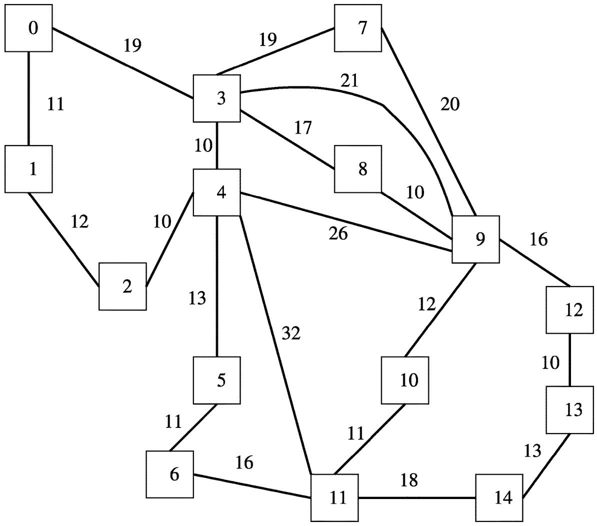

Fig. 3. Physical topology of the PacNet.

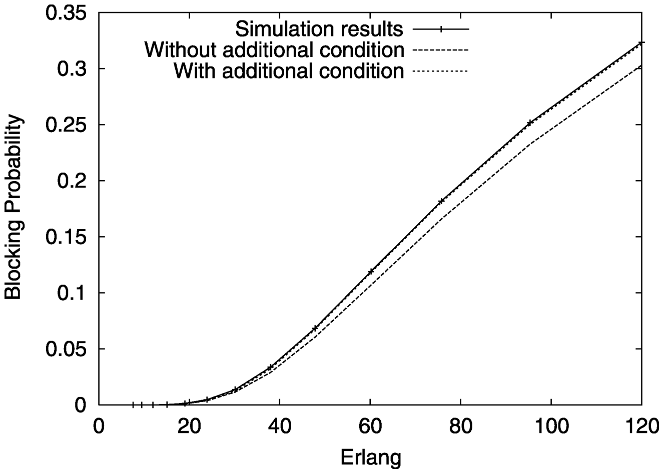

Fig. 4. Traffic blocking of the centralized method in the PacNet with and without the additional condition as shown in (28), respectively.

Fig. 4 demonstrates the proposed models' higher accuracy in analyzing the "classic" centralized case under nonbursty traffic loads (The average duration of each connection is 10 000 s). We show that by taking the additional condition $X_j=m$ [as discussed in (28)] into consideration, we achieve more accurate analysis of state dependent arrival rate and, consequently, more accurate probability that some specific network capacity is in idle state, which finally leads to more accurate blocking analysis.

The more important issue is to examine the accuracy of the proposed models for distributed cases under highly bursty traffic loads. From now on, unless other specified, we let the average duration of each connection be equal to 100 ms, a typical value in WROBS networks.

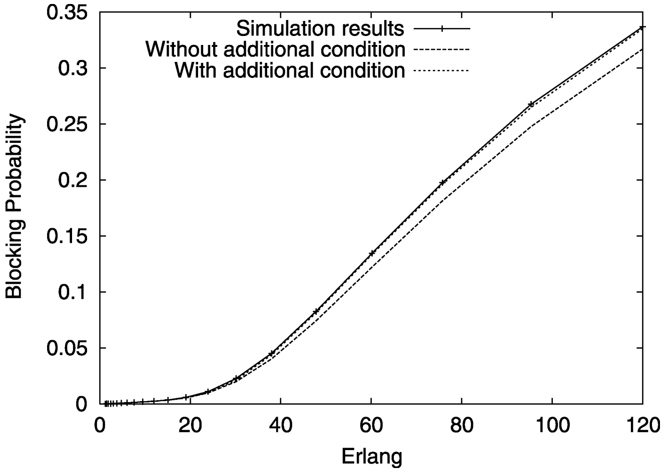

Fig. 5. Forward blocking of the DIR method in the PacNet with and without the additional condition as shown in (28), respectively.

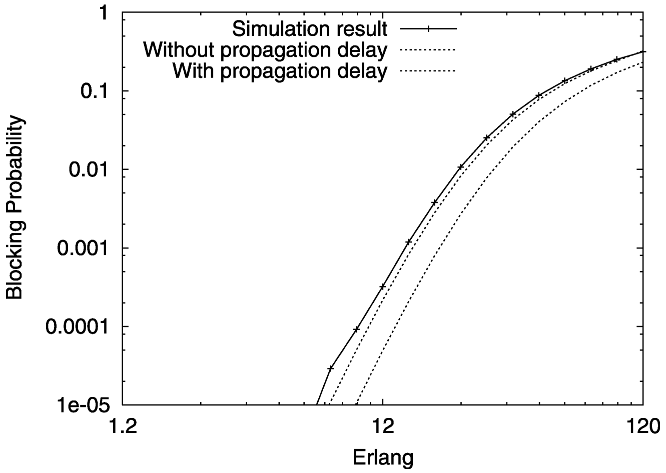

Fig. 6. Forward blocking of the DIR method in the PacNet with and without considering the propagation delay, respectively. The average duration of each connection is 10 ms.

Fig. 5 and Fig. 6 examine the accuracy in analyzing blocking due to insufficient network capacity (forward blocking of the DIR method). Fig. 5 compares the analysis results with and without the additional condition $X_j = m$, respectively. Similar to that in the centralized case, with more accurate analysis of state dependent arrival, the accuracy of the network blocking analysis could be significantly improved, especially under heavy traffic load. Fig. 6 shows the improvement of accuracy that can be achieved by taking the propagation delay into account. As we have mentioned, due to the propagation delay, some network capacity has to be reserved for a short period of time before the data transmission begins. This type of "capacity waste" is more significant when connection requests arrive at a high rate with a short average duration. By taking this fact into consideration, we could achieve higher accuracy in blocking analysis. Fig. 6 shows the results when the average duration of each connection request is 10 ms. Under very heavy traffic loads, however, most of the traffic blocking is caused by insufficient network capacity, thus the effects of propagation delay become less significant. That explains why the two analytical models tend to merge under heavy traffic loads.

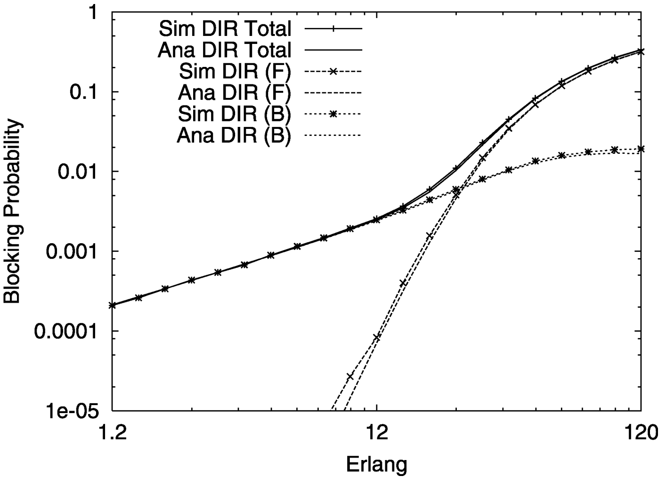

Fig. 7. Blocking analysis of the DIR method in the PacNet (both the forward and the backward directions).

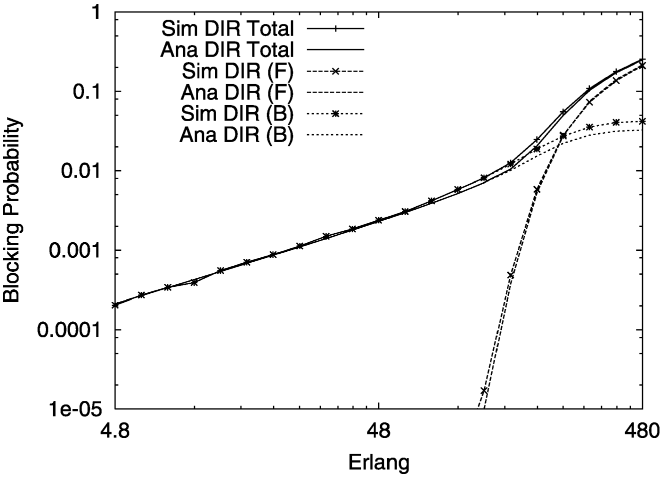

Fig. 8. Blocking analysis of the DIR method in the PacNet where there are 32 channels per fiber.

The analysis results of blocking probabilities in both the forward and the backward directions are presented in Fig. 7, which show a very good match with simulation results. In addition, we observe that under light traffic load, the blocking mainly takes place in backward direction, caused by outdated information; whereas under heavy traffic load, the blocking occurs mainly in forward direction, due to insufficient network capacity. Fig. 8 demonstrates the high accuracy of the analytical model when the number of wavelength channels per fiber is larger (32 channels per fiber).

To investigate how the blocking performance would be affected when the traffic load becomes more and more bursty, Fig. 9 deals with connection blocking when the traffic request arrival rate is higher and the average duration is shorter (10 ms). We find that in this case, the blocking probability in the backward direction is significantly higher compared to the case in Fig. 7. In other words, under more bursty traffic load, the blocking probability caused by outdated information is significantly higher. We observe that for this case, our analytical models can still achieve highly accurate results.

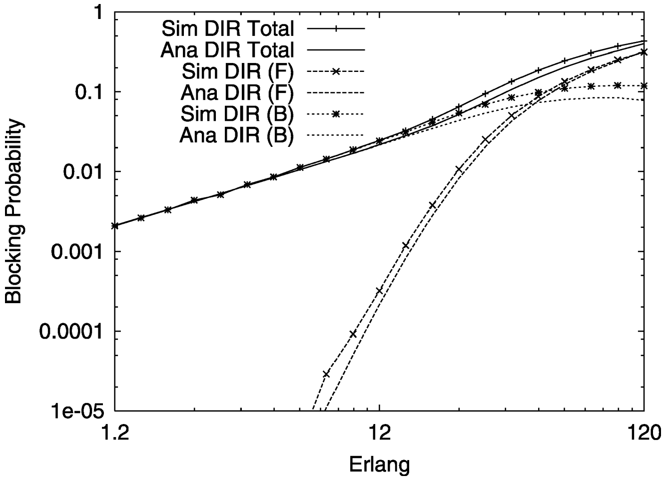

Fig. 9. Blocking analysis of the DIR method in the PacNet under highly bursty traffic, where the average duration of each connection is 10 ms.

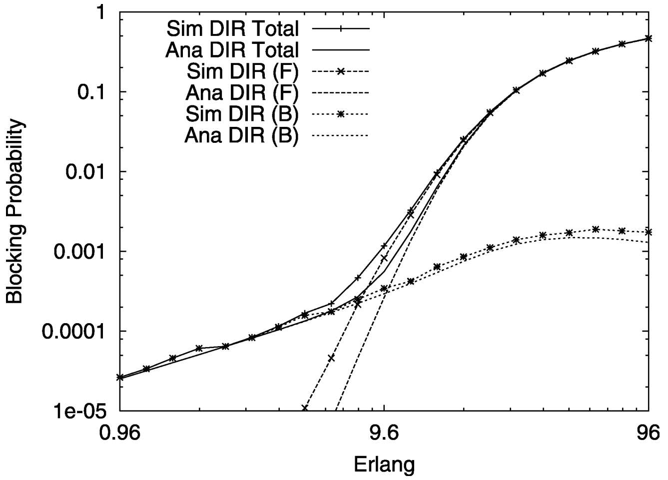

Fig. 10. Blocking analysis of the DIR method in the 12-node ring network.

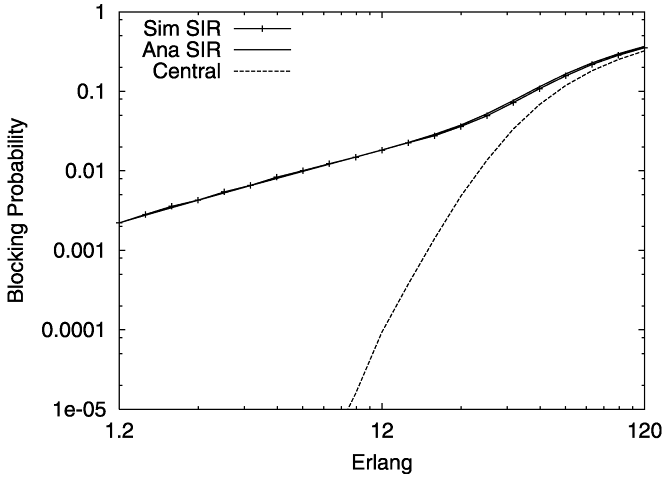

Fig. 11. Blocking analysis of the SIR method in the PacNet.

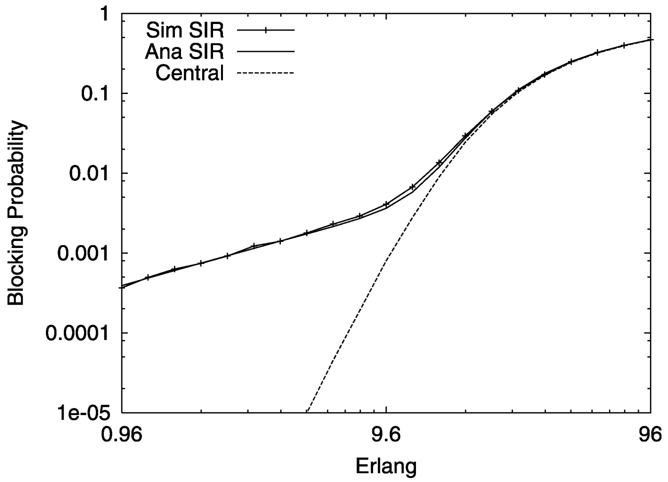

Fig. 12. Blocking analysis of the SIR method in the 12-node ring network.

The performance of the proposed analytical models on the optical ring is presented in Fig. 10. We observe that, due to the very high correlation between different lightpaths, the analysis results become less accurate compared to those in the PacNet (but still acceptable). In fact, this is also the case in most of the previous studies (e.g., [15]). To get more accurate results, it is widely believed that more complicated models have to be used, which in our case means that the assumptions we made before (9) shall be somewhat released. However, how to keep the complexity of computation at a reasonably low level when releasing these assumptions is basically still an open problem.

The accuracy of the analytical model for the SIR method is demonstrated in Fig. 11 and Fig. 12, respectively. We observe that, by taking into consideration the effects of over-reservation, we were able to get highly accurate analysis results for both the regular and irregular networks under either light or heavy traffic loads. To show the significance of the blocking caused by over-reservation, we include in these figures the curves of network blocking for centralized cases. The difference between the blocking of centralized cases and the blocking of SIR cases comes from over-reservation. We see that under light traffic loads, over-reservation is the dominant cause of traffic blocking, while under heavy traffic loads, insufficient network capacity causes most traffic blocking.

Besides the high accuracy, the computational efficiency of the proposed models also appears to be satisfying. On a Pentium III 450 PC with 128 M memory and Red Hat Linux 8.0 system, it generally takes only several seconds to get the analytical result under a specific traffic load. For example, for the case of using the DIR method in the PacNet with eight channels per fiber, it takes 1.642 s CPU time to get the analytical result where the average traffic load sourced from each node on each wavelength is 120 Erlang. As to the case of using the SIR method, it takes 1.214 s CPU time to get the analytical result under the same traffic load.

V. CONCLUSIONS

In this paper, we analyzed connection blocking in distributed wavelength-routed networks by studying two central schemes, DIR and SIR. We analyzed three different types of connection blocking: 1) blocking due to insufficient network capacity; 2) blocking due to outdated global information; and 3) blocking due to over-reservation. The latter two types of blocking would become increasingly important when we are handling more and more bursty traffic loads. Extensive simulation results showed that our analytical models achieve highly accurate results for both schemes, in both regular and irregular network topologies, under both light and heavy traffic loads. By studying the fundamental types of connection blocking in the two central schemes, this analysis also offers a first insight into blocking behavior of distributed lightpath establishment schemes, since the connection blocking cases studied here are incurred in one combination or another in most schemes, due to the fundamental nature of the distributed process involved in setting up lightpaths.

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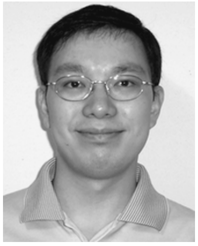
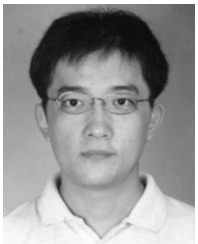


Kejie Lu (S'01–M'04) received the B.S. and M.S. degrees in telecommunications engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 1994 and 1997, respectively, and the Ph.D. degree in electrical engineering from the University of Texas, Dallas, in December 2003.

He is now a Postdoctoral Research Associate at the Department of Electrical and Computer Engineering, University of Florida, Gainesville. His research interests include architecture and protocols design in WDM optical networks and wireless networks, performance analysis, and wireless communications systems.



Gaoxi Xiao (M'99) received the B.S. and M.S. degrees in applied mathematics from Xidian University, Xi'an, China, in 1991 and 1994, respectively, and the Ph.D. degree from the Department of Computing, Hong Kong Polytechnic University, in 1999.

From 1994 to 1995, he was with the Institute of Antenna and Electromagnetic Scattering, Xidian University. In 1999, he was a Postdoctoral Fellow in the Department of Electronic Engineering, Polytechnic University, Brooklyn, NY. During 1999–2001, he was a visiting scientist with the Center for Advanced Telecommunications Systems and Services (CATSS), University of Texas, Dallas. Since October 2001, he has been an Assistant Professor with the Division of Communication Engineering, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His research interests include optical and wireless networking, distributed systems, and algorithm design and analysis.

Imrich Chlamtac (F'93) received the Ph.D. degree in computer science from the University of Minnesota, Minneapolis.

Since 1997, he has been the Distinguished Chair in Telecommunications at the University of Texas, Dallas. He holds the titles of the Sackler Professor at Tel Aviv University, Israel, The Bruno Kessler Honorary Professor at the University of Trento, Italy, and University Professor at the Technical University of Budapest, Hungary. He has published over 300 papers in refereed journals and conferences, and is the co-author of the first textbook on *Local Area Networks* (Lexington Books, 1981, 1982, 1984) and of *Mobile and Wireless Networks Protocols and Services* (Wiley, 2000).

Dr. Chlamtac is a Fellow of the ACM, a Fulbright Scholar, and an IEEE Distinguished Lecturer. He is the winner of the 2001 ACM Sigmobile annual award and the IEEE ComSoc TCPC 2002 award for contributions to wireless and mobile networks, and of multiple best paper awards in wireless and optical networks. He serves as the founding Editor-in-Chief of the *ACM/URSI/Kluwer Wireless Networks (WINET)*, the *ACM/Kluwer Mobile Networks and Applications (MONET)*, and the *SPIE/Kluwer Optical Networks (ONM) Magazine*.