An Evaluation of Distributed Parallel Reservations in Wavelength-Routed Networks

Jian Liu, Gaoxi Xiao, Kejie Lu, and Imrich Chlamtac

Abstract

Distributed lightpath provisioning is expected to play a key role in next-generation WDM optical networks. A major challenge in distributed lightpath provisioning is the potentially significant degradation of network blocking performance caused by outdated link-state information, occurring especially under traffic with short average durations of connections. To address this problem, various *parallel reservation* schemes have been proposed, with the common feature of applying multiple capacity-search and/or reservation operations executed simultaneously. In this paper, we evaluate the performance of these distributed parallel reservation schemes in wavelength-routed networks. Specifically, we develop general yet accurate analytical models to provide insights into the behavior of the different schemes. We also conduct extensive simulation study. Numerical results show that by using simple parallel reservation schemes, in particular through multiple reservations on several different routes, blocking probabilities caused by outdated link-state information can be drastically lowered and network performance can be significantly improved. The tradeoff between control traffic loads and network blocking performance is also evaluated.

Index Terms

Wavelength-routed network, distributed lightpath provisioning, parallel reservations.

J. Liu and G. Xiao are with Network Technology Research Centre, School of Electrical and Electronic Engineering, Nanyang Technological University Singapore 637553. Email: {PG02310397, egxxiao}@ntu.edu.sg.

K. Lu is with the Department of Electrical and Computer Engineering, University of Puerto Rico at Mayagüez, Mayagüez, PR 00681, USA. Email: lukejie@uprm.edu.

I. Chlamtac is with CreateNet and the University of Texas at Dallas, Richardson, TX 75083. Email: chlamtac@create-net.it

I. Introduction

Wavelength-division multiplexing (WDM) is an important technology for handling tremendous bandwidth demands of backbone metro and long haul networks. It is generally believed that the majority of future WDM networks will be *wavelength-routed networks*, where different network nodes communicate with each other via end-to-end all-optical connections known as *lightpaths* [1], [2]. The procedure of establishing such connections is called *lightpath provisioning*. In the absence of wavelength conversion, the same wavelength must be used on every hop along the route, known as the *wavelength-continuity constraint* [1].

Traditional backbone optical networks provide static lightpath provisioning where a lightpath, once established, is expected to remain for a long time. In the next-generation optical networks, however, traffic loads will become more dynamic, and consequently lightpaths have to be set up and torn down more frequently. In the extreme case of *wavelength-routed optical burst-switched* (WROBS) networks [3], for example, it is expected that the duration of each lightpath will be at the sub-second time scale. As a result, the *Dynamic Lightpath Establishment* (DLE) problem [4] is becoming increasingly important.

To handle DLE in wavelength-routed networks, network control can be either *centralized* or *distributed*. Centralized control achieves efficient utilizations of network resources in small- or medium-sized networks with static traffic loads. However, in large networks or networks with dynamic traffic loads, a single central controller responsible for collecting all the information and making all the decisions can easily be overloaded and the distribution of status and control information in both directions between the controller and the nodes takes prohibitively long time. To cope with the rapid growth of optical networks, distributed control is therefore becoming increasingly important and is being standardized within the *Generalized Multi-Protocol Label Switching* (GMPLS) framework [5]. Unlike centralized DLE, distributed DLE allows decision-making intelligence to be distributed among network elements, where each node in the network can make its own decisions. To facilitate the decision making, link-state information is generally exchanged between different network nodes.

The exchanges of link-state information can be conducted by flooding or broadcasting. In such cases, each node can have a local database to store all the link-state information it needs and makes its own routing decisions based on the information it has [6], [7]. Alternatively, link-state information can be collected upon request when a lightpath needs to be set up. The basic methods belonging to the second class include the *source-initiated reservation* (SIR) method and the *destination-initiated reservation* (DIR) method [8]. In the SIR method, when a lightpath needs to be set up, the source node sends out a connection request to the destination node, reserving some capacities along the route. The destination node then selects a wavelength that has been successfully reserved (if available) and sends a confirmation request to confirm the reservation and release the other reserved capacities (if any). A critical issue of the SIR scheme is the number of wavelengths reserved on each link along the route. If too many wavelengths are reserved, network capacities could be wasted, leading to the *over-reservation* problem [9]. If too few wavelengths are reserved, the request may be blocked even though a free wavelength is available along the route.

In the DIR method, the connection request does not reserve any capacity. Instead, it collects the link-state information along the route. Based on the information it carries, the destination node would select an appropriate wavelength (if applicable), and send a reservation request to reserve the selected wavelength along the route. By doing so, the over-reservation problem is eliminated. It has been shown that the DIR method generally outperforms the SIR method [8].

A major challenge in distributed lightpath provisioning is that, unavoidably, network nodes may have *outdated* link-state information, either because link-state information is exchanged only periodically, or due to the propagation delay along the links. In [9] [10], by using the DIR method as a case study, it is demonstrated that blocking due to outdated information dominates the network performance under light, highly dynamic traffic loads. Specifically, when a reservation request reaches a link intended to reserve a certain wavelength, it may find that the wavelength that was available when the connection request arrived has in the meantime been reserved by another, earlier arrived, reservation request. In [11], it is shown that in wavelength-routed networks with periodical link state flooding, effects of outdated information remain to be dominant under light traffic loads.

Several schemes have been proposed to reduce the impact of outdated link-state information on network-blocking performance. In [12], [13], the authors propose to activate re-routing operations when there is blocking due to outdated information. In [14], a framework termed *intermediate-node initiated reservation* (IIR) is proposed where reservations can be initialized at any set of nodes along the route, before the connection request reaches the destination node, such that the probability of having outdated link-state information due to propagation delay is lowered.

Schemes have also been proposed to deploy *parallel* capacity-searching and/or reservation operations, to increase

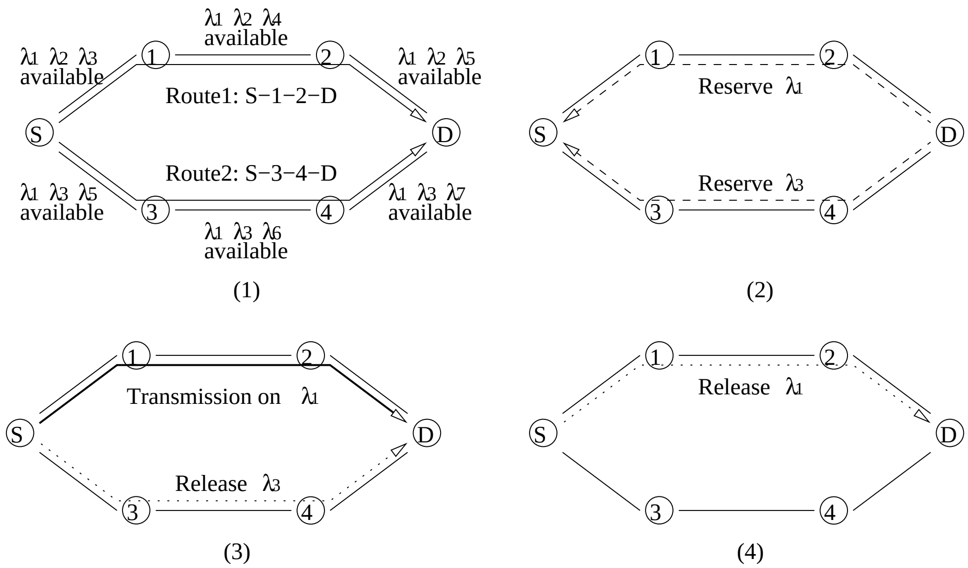


Fig. 1. An example of the MPPR scheme where we have two candidate routes and one reservation on each route (i.e., the 2P-2R scheme).

the chance that at least one of them is successful despite of the existence of outdated information. Specifically, in [15], [16], Shami *et al.* propose to send out multiple connection requests (i.e., parallel capacity searching) but only a single reservation request for setting up a connection. Similar schemes have also been adopted in Quality-of-Service (QoS) routing in packet-switched networks [17] and restoration in WDM networks [18]. Though they increase the chance that at least one connection request could successfully reach the destination node, parallel capacity searching alone cannot lower the dominant effects of outdated information on the reservation requests. Parallel capacity reservations help to significantly improve the performance of the SIR scheme. Other than that, however, existing results on parallel reservations in wavelength-routed networks are rather limited. In [19], the IIR scheme [14] has been extended to allow parallel reservations of multiple wavelengths on the same route. In [20], a general framework termed *Multi-Path Parallel Reservation* (MPPR) was studied. Specifically, to set up a lightpath, the source node can either send out a single connection request, as in the classic DIR method, or multiple connection requests along multiple different routes simultaneously. The destination node, upon receiving the connection requests, can respond to some or all of them, reserving on each route one or multiple wavelengths. Fig. 1 illustrates a special case of MPPR where there is one reservation on each of the two candidate routes. Preliminary results in [19] and [20] show that a correct number of parallel reservations significantly lowers network blocking under light, highly dynamic traffic. Too many parallel reservations, on the other hand, lead to high control overhead and may actually increase network blocking by over-reserving network capacities.

Parallel capacity-search and reservation operations are not only effective in helping lower the blocking probability of distributed DLE, they may also contribute to enhance the next-generation optical Internet. For example, in optical Internet with combined advance reservation and immediate reservation [21], parallel capacity-search operations allow each immediate reservation to choose from several candidate routes the best one. In networks with impairment-awareness request [22], parallel search and reservation enables the comparisons of signal quality along several different routes such that the qualified one(s) can be selected.

In this paper, we focus on studying DLE methods with parallel operations. By using the MPPR method as a case study, we evaluate the performance of parallel reservations in distributed wavelength-routed networks. We develop general yet accurate analytical models and conduct extensive simulations for validation. Analytical and simulation results provide insightful understandings of the performance of different parallel reservation schemes under different traffic loads. Discussions of the different schemes' control overheads are also provided.

The paper is organized as follows. In Section II, we present the general framework of MPPR and then describe several specific schemes which we would evaluate in details later. Analytical models are proposed in Section III following a brief survey of related existing results. Section IV presents numerical results and discussions. Section V concludes the paper.

II. Multi-Path Parallel Reservation Schemes

We choose the rather general multi-path parallel reservation (MPPR) method as a case study, such that the main idea for developing analytical models as well as most observations would remain valid for many other parallel reservation schemes.

A. Framework of the Multi-Path Parallel Reservation Method

The framework of the MPPR method can be described as follows. To set up a lightpath, the source node sends out a certain number of connection requests along a set of alternative routes, one request on each route. Upon the arrival of a connection request, the destination node could either simply drop it, or send a reservation request back to the source node, reserving one or multiple wavelengths along this route.

Once the first successful reservation request reaches the source node, data transmission starts immediately on one of the reserved wavelengths, while the other reserved wavelengths on the same route (if any) are released. Later when the other reservation requests (if any) arrive, immediate release requests will be initialized in response.

B. Several Specific MPPR Schemes

In MPPR, a good balance needs to be kept between network performance and control overhead. As mentioned earlier, too many parallel reservations lead to high control overheads, and may actually degrade network blocking performance. To keep control overhead at an acceptable level, we consider only those MPPR schemes subjecting to the following conditions:

- To establish a lightpath, there could be at most two connection requests on two link-disjoint alternative routes.
- On each route, a reservation request can reserve at most two wavelengths.

The first constraint also helps reduce the average length of each lightpath, since the third link-disjoint route between a pair of nodes, if exists at all, is typically quite long in a sparse network. The second constraint is adopted because of the following reasons: 1) having more reservations per route may lead to significant over-reservations, which degrades the network performance under heavy traffic loads; 2) under medium and light traffic loads, reserving two wavelengths can sufficiently reduce the blocking caused by outdated information as later we will see, thus reserving more wavelengths is not necessary.

Specifically, we discuss several schemes as follows:

- *Single-path single-reservation* (1P-1R) method, i.e., the classic DIR method. This classic method provides a benchmark for our performance evaluations.
- *Single-path double-reservation* (1P-2R) method is nearly the same as the 1P-1R method except that each reservation request can reserve two wavelengths (if such are available) along the route. If both wavelengths are successfully reserved, one of them will be randomly selected for data transmission while the other one would be released immediately.
- *Alternate-path single-reservation* (2P-1R) method, where there are two connection requests on two link-disjoint routes, yet only a single reservation request in response to the first successful connection request, reserving one wavelength along its route. This method is the same as the method proposed in [16].
- *Alternate-path double-reservation* (2P-2R) method, which sends out two connection requests on two alternative routes, and one reservation request in response to each successful connection request, reserving one wavelength on each route. The example in Fig. 1 demonstrates the 2P-2R method.
- *Alternate-path four-reservation* (2P-4R) method is similar to the 2P-2R method, except that each reservation

request reserves two wavelengths (if applicable) along its route. Therefore the source node needs to release a maximum of three reserved wavelengths.

III. An Analytical Model

Blocking probability has traditionally been used as a key metric for measuring the performance of wavelength-routed networks. Various models have been developed for analyzing the network blocking performance. In this section, following a brief survey of the existing results, we propose our new models. To the best of our knowledge, this is the first time distributed *parallel* reservation schemes are analyzed. The model is applicable to virtually all schemes within the MPPR framework, while its main idea applies to analyzing many other distributed parallel reservation schemes.

A. Previous Work

Extensive research has been conducted on analyzing centralized-controlled lightpath provisioning. Existing results generally aim to achieve higher accuracy (e.g., by carefully measuring the effects of traffic correlations [23]–[26]), or to simplify analytical model without significantly sacrificing accuracy (e.g., [27]). The most significant contributions include (i) the adoption of the *reduced load approximation* approach [28] with the *state-dependent arrival model* [29] in blocking analysis [23]; and (ii) the evolution from link-independent to link-correlation model [24] (which later was greatly simplified in [27]), etc. A comprehensive survey of the existing results can be found in [9]. While most of the previous work has been done for fixed routing schemes, alternative-path routing schemes [27], [30], [31], dynamic routing schemes [32], [33], and the more general case under heterogeneous traffic [34] have also been analyzed.

The first analytical model for distributed lightpath provisioning is proposed in [10], where the effect of outdated link-state information is taken into consideration. However, by adopting the link independent assumption, the analytical model is rather simple but not very accurate. The analysis accuracy is later improved in [9], where link correlation and effects of propagation delay are calculated. Both of these results consider the classic DIR method where a single reservation request is initialized for establishing a lightpath. In the next subsection, we extend them to analyzing parallel reservation schemes requiring nontrivial modifications.

B. Analytical Models of Parallel Reservation Schemes

Compared to the analysis of the classic DIR method, blocking analysis of parallel reservation schemes requests nontrivial extensions, mainly because of the strong correlations between the parallel reservation operations. Specifically,

- For the cases where *not* every connection request initializes a reservation request, whether to initialize a reservation request or not generally depends on the status of the other reservation requests between the same source-destination nodes. Such strong correlations greatly complicate the blocking analysis.
- When multiple wavelengths are reserved for setting up a lightpath, either on a single route or on multiple candidate routes, their respective durations are strongly correlated. In fact, all but one of them will be released shortly. These temporary reservations, however, still consume some network capacities. Under traffic with short durations of connections, such kind of capacity consumptions may significantly affect the network performance and therefore cannot be neglected.
- For the cases where there are multiple parallel reservations for setting up a connection between each pair of source-destination nodes, arrivals of reservation requests are not Poisson-distributed. Such kind of non-Poisson distributions are difficult to analyze, especially when the multiple reservations are on a same route leading to even stronger correlations.

We start by considering the relatively simple cases where each successful connection request initializes a *single* reservation request reserving a *single* wavelength on its route. We see that among the specific schemes listed in Section II-B, 1P-1R and 2P-2R methods belong to this category. Discussions on such cases form a basis for further extensions to analyzing the otherwise cases, as later we will see.

To address these problems, we introduce the concept of *attempting connection*. Specifically, we define each nP-nR ($n \geq 1$) reservation operation as composed of n attempting connections, each of which containing a single connection request and a single reservation request attempting to set up a single lightpath, just as that in the classic DIR method. For example, a 2P-2R operation could be viewed as composed of two attempting connections. By doing so, the case with only one of two connection requests reaching the destination could be viewed as having one attempting connection blocked in the *forward direction* (i.e., the direction from the source to the destination); while the case with only one of two reservation requests successfully reaching the source could be viewed as having one attempting connection blocked in the *backward direction* (i.e., the direction from the destination to the source). More significantly, by introducing this definition, a temporary reservation (if any) could be viewed as a successful attempting connection with *zero* data-transmission duration. Therefore, parallel reservation schemes could be viewed as extensions of the classic DIR scheme where *arrivals* and *durations* of attempting connections are strongly correlated. Since fully reflecting all the correlation effects would make blocking analysis prohibitively complicated, to keep a balance between complexity and accuracy, we take some correlation factors into account while making assumptions to simplify the others. Specifically,

- We approximate the non-Poisson *arrivals* of parallel reservations as a Poisson process. In other words, n parallel reservations between a same pair of source-destination nodes are approximated as n attempting connections arriving from a Poisson process. Though this approximation tends to underestimate the burstiness of reservation operations, it greatly simplifies the analytical model. As later we would see, analysis results remain as highly accurate in both mesh- and ring-topology networks.
- The strong correlations between the *durations* of different attempting connections, on the other hand, are carefully reflected in the model, as later we will present in details.

Next we discuss the proposed analytical model in details.

1) Assumptions

We adopt the following assumptions in our analysis:

- The network consists of J links connected in an arbitrary fashion.
- Each link has C wavelengths.
- Between each source-destination node pair S, there are n_s attempting connections, indexed from 1 to n_s in an increasing order of their respective length of routes. To break a tie, the attempting connection leading to lightpath establishment (if any) is assigned the smallest index while the others are assigned randomly. To simplify the analysis, throughout this paper we assume that successful connection requests on lower-indexed routes always reach the destination node earlier. As long as no confusion would be caused, we denote the i-th attempting connection between node pair S, $1 \leq i \leq n_s$, as well as its route as $R(i)$. When there is no need to specify the index of an attempting connection, we denote the attempting connection as well as its route as R.

- The duration of each data transmission follows the exponential distribution with an average interval of $1/\mu$.
- There is no wavelength conversion in the networks. Therefore the wavelength-continuity constraint applies.
- The wavelength assigned to each attempting connection is randomly selected from the set of wavelengths that are available along the route.

To simplify the descriptions, we use the same notations as those in [9]. Specifically, we call the blocking in the forward direction the *forward blocking*; and the blocking in the backward direction the *backward blocking*. Between the two end nodes of each link along 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. We let the *link state* be the state of a link when a connection request reaches the right-hand node of the link. We define that a wavelength channel can be in one of the following three states: (1) free; (2) reserved, yet 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*.

2) Framework of the Analytical Model

Following [9], we let X_j $(j = 1, 2, \cdots, J)$ be the random variable representing the number of idle wavelength channels on link j. Let

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

be the probability that there are exactly m idle wavelength channels on link j. Following [29], we assume that all X_j's are mutually independent, that is,

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

where

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

We further assume that when there are m idle wavelength channels on link j, the inter-arrival time of attempting connections is exponentially distributed with a parameter $\alpha_j(m)$, which is called the *state dependent arrival rate* [29]. Note that, in our analysis, there are some *zero*-duration attempting connections. We introduce a parameter $\rho_j(m)$, which denotes the probability that an attempting connection passing through link j is of a *non-zero* duration,

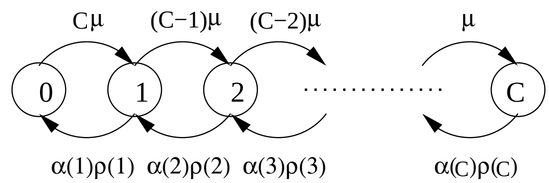


Fig. 2. The birth-death process of different link states in wavelength-routed networks with distributed parallel reservations.

given that there are m idle wavelengths on the link. It then follows that the number of idle wavelengths on link j can be modeled as the outcome of a birth-death process as shown in Fig. 2. Specifically, we have

$$q_j(m) = \prod_{k=1}^{m} \frac{C-k+1}{\alpha_j(k)\cdot\rho_j(k)} \cdot \mu^m \cdot q_j(0), \quad m = 1, 2, \cdots, C \tag{3}$$

where

$$q_j(0) = \left[1 + \sum_{m=1}^{C} \prod_{k=1}^{m} \frac{C-k+1}{\alpha_j(k)\cdot\rho_j(k)} \cdot \mu^m\right]^{-1}. \tag{4}$$

Finally, the framework of the analytical model can be summarized as follows:

◇ **Analytical Model: Framework**

1) Initialize $\alpha_j(m)$ and $\rho_j(m)$, $j = 1, 2, \cdots, J$ as follows

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

$$\rho_j(m) = \begin{cases} 1 & m = 1, 2, \cdots, C, \\ 0 & m = 0. \end{cases} \tag{6}$$

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

3) Calculate the blocking probability of the attempting connections between node pair S as follows:

$$B_{R(i)} = B^F_{R(i)} + (1 - B^F_{R(i)}) \cdot B^B_{R(i)}, \quad i = 1, 2, \cdots, n_s \tag{7}$$

where $B^F_{R(i)}$ and $B^B_{R(i)}$ denote the forward blocking probability and the backward blocking probability of the attempting connection $R(i)$, respectively.

4) Calculate the blocking probability of node pair S as

$$B_S = \prod_{i=1}^{n_s} B_{R(i)}. \tag{8}$$

If for every node pair S, B_S has been convergent, then stop; otherwise, go to step 5).

5) Update $\alpha_j(m)$ and $\rho_j(m)$, $j = 1, 2, \cdots, J$ as follows:

$$\alpha_j(m) = \sum_{R:j\in R} \lambda_{R,j}(m) = \sum_{R:j\in R} \lambda_R(1 - B_{R|X_j=m}) \tag{9}$$

where $\lambda_{R,j}(m)$ denotes the arrival rate of the successful attempting connections on route R (including those with zero data transmission duration), given that the state of link j is m.

$$\rho_j(m) = \frac{\sum\limits_{R:R\in R_j^{(1)}} (1 - B_{R|X_j=m}) + \sum\limits_{i=2}^{n_s} \sum\limits_{R:R\in R_j^{(i)}} \left((1 - B_{R|X_j=m}) \cdot \prod\limits_{l<i} B_{R(l)} \right)}{\sum\limits_{R:j\in R} (1 - B_{R|X_j=m})} \tag{10}$$

where $R_j^{(i)}$, $i \in \{1, 2, \cdots, n_s\}$, denotes the set of the i-th attempting connections passing through link j, $B_{R(l)}$ denotes the blocking probability of the attempting connection $R(l)$, and $B_{R|X_j=m}$ denotes the conditional blocking probability of the attempting connection on route R given that the state of link j is m. The calculations of $B_{R|X_j=m}$ remain the same as those in [9]. Go to step 2).

Remark: Eq. (10) reflects the correlations between two different parts of successful attempting connections: those finally leading to lightpath establishments, and those temporary ones.

We next discuss the calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$, respectively.

3) Calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$

The calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$ could be viewed as extensions of the models proposed in [9]. Specifically, let $h_{n,R(i)}$ denote the probability that a given set of n wavelength channels are free on route $R(i)$ at the moment when the connection request reaches the destination node. Since there is only a single reservation on each route, calculations equations proposed in [9] can be adopted without any change. Specifically,

$$B_{R(i)}^F = 1 - \sum_{n=1}^{C} (-1)^{n+1} \binom{C}{n} h_{n,R(i)}, \tag{11}$$

where

$$h_{n,R(i)} = \begin{cases} h_{n,1} & \text{if } L_{R(i)} = 1, \\ h_{n,1} \cdot \prod_{j=2}^{L_{R(i)}} h_{n,j|n,j'}(t_j) & \text{otherwise.} \end{cases} \tag{12}$$

In this equation, $L_{R(i)}$ denotes the hop length of route $R(i)$; link j and link j' denote the j-th and $(j-1)$-th (where $L_{R(i)} > 1$) link of route $R(i)$, respectively; and $h_{n,j|n,j'}(t_j)$ denotes the conditional probability that a given set of n wavelengths are free on link j, given that t_j time slots ago they were free on link j', where t_j denotes the propagation delay on link j.

For the backward blocking, if $L_{R(i)} = 1$, obviously $B^B_{R(i)} = 0$. When $L_{R(i)} > 1$, we have

$$B^B_{R(i)} = 1 - \prod_{j=1}^{L_{R(i)}-1} w_{j,j''}(t_{R(i)}(j)), \tag{13}$$

where j'' denotes the $(j+1)$-th link of route $R(i)$, and $w_{j,j''}(t_{R(i)}(j))$ denotes the conditional probability that no interfering reservation request has arrived link j within the past $t_{R(i)}(j)$ time slots and reserved the same wavelength channel, given that j'' is not on the route of that interfering request. Here $t_{R(i)}(j)$ denotes the round-trip propagation delay between the right-hand node of link j and destination node of route $R(i)$.

The calculations of $w_{j,j''}(t_{R(i)}(j))$, $h_{n,R(i)}$ and $h_{n,j|n,j'}(t_j)$ can be found in [9].

4) Extensions to the Cases Where There Are Multiple Reservations on Each Route

We now extend the proposed model to analyze the cases where there are $n_{R(i)}$ ($n_{R(i)} > 1$) parallel reservations on the same route $R(i)$. Among the specific schemes listed in Section II-B, 1P-2R and 2P-4R schemes belong to such cases. By viewing parallel reservations on a same route as separate attempting connections, we refine Eq. (11) by adopting the *Jordan Theorem* [35] as follows:

$$\begin{aligned} B^F_{R(i)_k} = 1 - \sum_{n=k}^{C} (-1)^{n-k} \cdot \binom{n-1}{n-k} \cdot \binom{C}{n} \cdot h_{n,R(i)}, \\ k = 1, 2, \cdots, n_{R(i)}, \end{aligned} \tag{14}$$

where $R(i)_k$ denotes the k-th attempting connection on route $R(i)$. By doing so, we measure the probability of having fewer than m free wavelengths along the route. Another change that needs to be made is to let

$$B^F_{R(i)_k|x_j=m} = \begin{cases} 1 & \text{if } m < k, \\ 1 - \sum_{n=k}^{C} (-1)^{n-k} \cdot \binom{n-1}{n-k} \cdot \binom{C}{n} \cdot h_{n,R(i)|x_j=m} & \text{otherwise,} \end{cases} \tag{15}$$

where $k = 1, 2, \cdots, n_{R(i)}$.

Note that the calculations of backward blocking could also be affected where there are parallel reservations on a same route. Specifically, the wavelength assignment of each reservation operation is not strictly “random” since different reservations on a same route have to target different wavelengths. Taking this effect into consideration, however, makes the analytical model rather complicated. Therefore, we neglect this factor in our analysis, which generally leads to slight under-estimations of the backward blocking probability.

The strong correlations between *forward* blocking of different attempting connections, however, cannot be neglected. Specifically, if the first attempting connection on a route is blocked, all the other attempting connections on the same route will be blocked (since the attempting connection leading to lightpath establishment is assigned the smallest index among all the attempting connections on a same route). In other words, the forward blocking of a route $R(i)$ equals to the forward blocking of the first attempting connection on this route. By assigning smaller indexes to those attempting connections blocked in backward direction followed by those blocked in forward direction, we revise Eq. (7) as follows:

$$B_{R(i)} = B^F_{R(i)_1} + \sum_{l=1}^{n_{R(i)}-1} \left\{ \prod_{k=1}^{l} \left[\left(1 - B^F_{R(i)_k}\right) \cdot B^B_{R(i)_k} \right] \cdot B^F_{R(i)_{l+1}} \right\} + \prod_{k=1}^{n_{R(i)}} \left(1 - B^F_{R(i)_k}\right) \cdot B^B_{R(i)_k}, \quad i = 1, 2, \cdots, n_s. \tag{16}$$

Finally, Eq. (10) also needs to be revised to reflect the fact that a successful attempting connection is of a non-zero data-transmission duration if and only if 1) it is of the smallest index among all the attempting connections on its route; and 2) attempting connections on shorter routes between the same source-destination nodes have all been blocked. We have

$$\rho_j(m) = \frac{\sum_{R:R=R^{(1)}_{(1)}} (1 - B_{R|X_j=m}) + \sum_{i=2}^{n_R} \sum_{R:R=R^{(1)}_{(i)}} \left((1 - B_{R(i)|X_j=m}) \cdot \prod_{l<i} B_{R(l)} \right)}{\sum_{R:j\in R} \sum_{n=1}^{n_{R(i)}} \left[n \cdot B_{R^n|X_j=m-n} \cdot \prod_{k=1}^{n} \left(1 - B_{R_k|X_j=m-k+1}\right) \right]} \tag{17}$$

where n_R denotes the number of candidate routes between the same source-destination nodes, $R = R^{(1)}_{(i)}$ denotes that R is of the smallest index among all the successful attempting connections on route $R(i)$, and $B_{R^n|X_j=m-n}$ denotes the probability of having exactly n ($1 \le n \le n_{R(i)}$) successful attempting connections on route $R(i)$,

$$\begin{aligned} B_{R^n|X_j=m-n} = \; & B^F_{R(i)_{n+1}|X_j=m-n} \\ & + \sum_{l=n+1}^{n_{R(i)}-1} \left\{ \prod_{k=n+1}^{l} \left[\left(1 - B^F_{R(i)_k|X_j=m-n}\right) \cdot B^B_{R(i)_k|X_j=m-n} \right] \cdot B^F_{R(i)_{l+1}|X_j=m-n} \right\} \\ & + \prod_{k=n+1}^{n_{R(i)}} \left(1 - B^F_{R(i)_k|X_j=m-n}\right) \cdot B^B_{R(i)_k|X_j=m-n}. \end{aligned} \tag{18}$$

5) Extensions to the Cases Where Not Every Successful Connection Request Initializes a Reservation

The analytical model can also be extended to analyze those schemes where *not* every successful connection request initializes a reservation request, e.g., 2P-1R. We call such kind of parallel reservation schemes as *non-aggressive reservation* schemes. To develop a single general model for analyzing all the different non-aggressive reservation schemes may not be feasible, especially for the cases where different connection requests are allowed to trigger different numbers (including zero) of reservation requests. Therefore, we restrict ourselves to discuss the important special case where reservations are triggered in response to the *earliest* successful connection requests, until either a total of n reservation requests have been initialized, or every successful connection request has been responded with a reservation.

We first study the scheme with at most *one* reservation request initialized on each route. For such case, an n_RP-nR operation, where $n_R > n \geq 1$, can be viewed as containing n attempting connections. For the i-th ($1 \leq i \leq n$) attempting connection, we have that its forward blocking probability equals to

$$B^F_{R(i)} = \Pr\{N_{SCR} < i\} = \sum_{k=0}^{i-1} \Pr\{N_{SCR} = k\} \tag{19}$$

where N_{SCR} denotes the number of successful connection requests. In other words, the i-th attempting connection is blocked in forward direction if and only if there are fewer than i connection requests successfully reaching the destination. The probability $\Pr\{N_{SCR} = k\}$ can be calculated by summing up the blocking probabilities of $\binom{n_R}{k}$ different cases where in each case only a specific set of k connection requests are *not* blocked in forward directions.

To calculate the backward blocking, we see that the i-th attempting connection has a backward blocking on the j-th route ($j \geq i$) if and only if the following three conditions are all satisfied:

1) There are $i-1$ successful connection requests on the first $j-1$ routes;
2) There is no forward blocking on the j-th route; and
3) There is backward blocking on the j-th route.

Calculations of all these three probabilities are straightforward. Denote the first probability as $\Pr\{N_{SCR} = i-1 | N_{\text{route}} = j-1\}$ where $i \leq j$; the second probability as $(1 - B^F_j)$; and the third probability as B^B_j . The probability that the i-th attempting connection has a backward blocking on the j-th route can be formulated as

$$B^B_{R(i)|j} = \begin{cases} 0 & i > j \\ \Pr\{N_{SCR} = i-1 | N_{\text{route}} = j-1\} \cdot (1 - B^F_j) \cdot B^B_j & i \leq j. \end{cases} \tag{20}$$

The overall backward blocking of the i-th attempting connection therefore can be formulated as

$$B^B_{R(i)} = \sum_{j=1}^{n_R} B^B_{R(i)|j}. \tag{21}$$

The 2P-1R scheme, as a special case with only one attempting connection, can be analyzed by adopting Eqs. (19) – (21). Specifically, the forward blocking is

$$B^F = B^F_{R(1)} \cdot B^F_{R(2)}, \tag{22}$$

and the backward blocking is

$$B^B = (1 - B^F_{R(1)}) \cdot B^B_{R(1)} + B^F_{R(1)} \cdot (1 - B^F_{R(2)}) \cdot B^B_{R(2)}. \tag{23}$$

The model can be further extended to handle the cases where there could be multiple reservations on each route. However, the detailed discussions, though not really difficult, are very lengthy. Therefore they are omitted in this paper.

Finally, the main contributions of the proposed analytical models can be summarized as follows:

- By introducing the concept of attempting connection, we provide a general framework for analyzing different parallel reservation schemes.
- By treating temporary connections as successful attempting connections with zero data-transmission duration and formulating the correlations between different attempting connections' durations, as shown in Eqs. (10) and (17), we propose a general method for analyzing the over-reservation effects in distributed parallel reservations.
- For analyzing the schemes where there are multiple reservations on a same route, we take into account the strong correlations between forward blocking of different attempting connections (Eq. (16)), while Jordan Theorem is also adopted (Eq. (14)) .
- Non-aggressive reservation schemes are analyzed by adopting the simple strategy of viewing each mP-nR reservation operation as composing of n attempting connections.

IV. Numerical Results and Discussion

In this section, blocking performance of several MPPR schemes is evaluated by extensive simulations and analyses, while the accuracy of the proposed analytical models is also verified. The simulations were conducted on PacNet (as shown in Fig. 3, where the numbers next to the links denote the physical lengths in tens of kilometers)

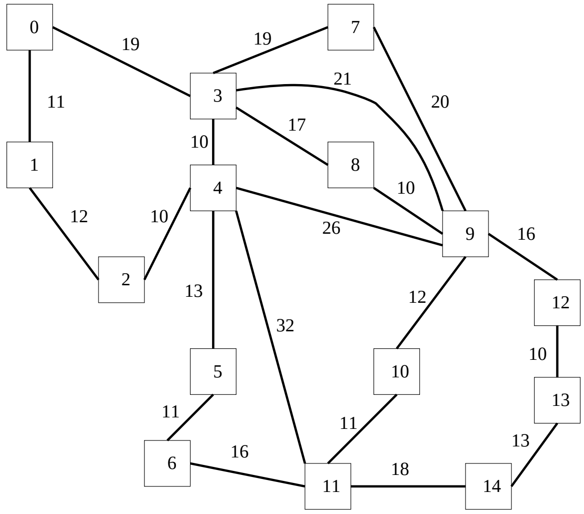
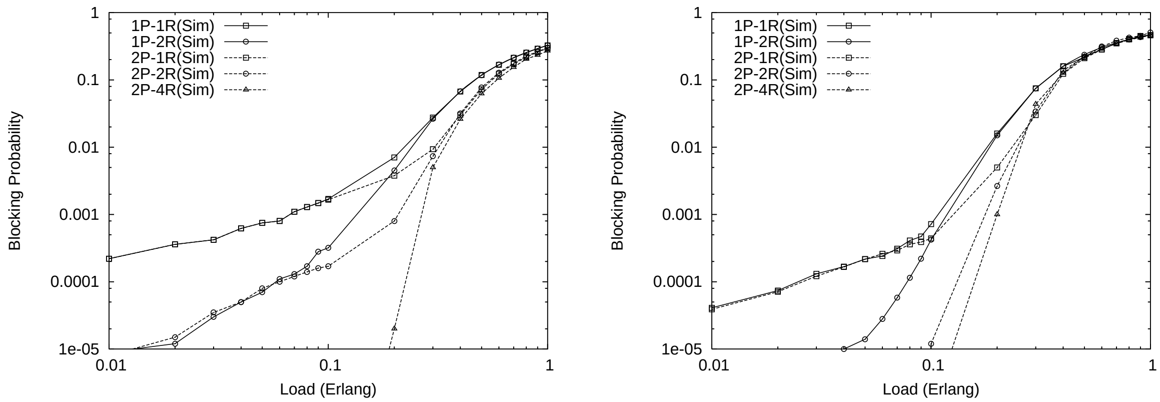


Fig. 3. Topology of the PacNet.

and a 12-node ring network (where the length of each link is 20 km), respectively. We assume that (1) each link is composed of two directional fibers of opposite directions, with eight wavelengths per fiber unless otherwise specified; (2) lightpath establishment requests are uniformly distributed between each pair of source-destination nodes with exponentially-distributed durations; and (3) random wavelength assignment is adopted by every reservation request. In [9], it is shown that under dynamic traffic with short average durations of connections, random wavelength assignment method outperforms the first-fit wavelength assignment method.

To better represent real-world scenarios, we further assume that (1) control messages are handled in the First-Come-First-Serve (FCFS) manner on each node, where the processing time of each connection/reservation/release request is $10\ \mu s$; (2) *parallel OXC* [36], which handles multiple switching operations in parallel, is employed on each node, with a switching time of $500\ \mu s$; and (3) a node always forwards a reservation request immediately after processing without waiting for the configuration of the local OXC, i.e., the *Forward before XC* (FBXC) scheme [36] is adopted.

To study the effects of proposed schemes, we run simulations for different cases with extra short (10 ms), short (100 ms) and long (1000 seconds) average durations of connections, respectively. The traffic loads are measured by the average traffic sourced from each node on each wavelength, ranging from 0.01 to 1 Erlang.



(a) PacNet (b) 12-node ring

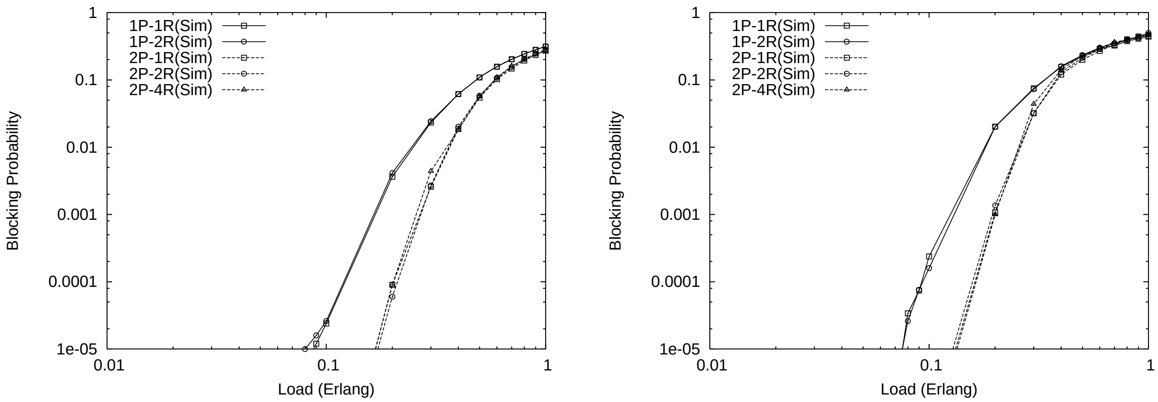
Fig. 4. Blocking performance of the different parallel reservations schemes under traffic with an average duration of connection of 100 ms.

A. Evaluation of the Blocking Performance

Fig. 4 plots blocking probabilities vs. traffic loads with a short average duration of connection for different MPPR schemes in different networks. Under light traffic loads, we see that 1P-2R, 2P-2R and 2P-4R significantly outperform 1P-1R and 2P-1R. In other words, by having multiple parallel reservations, either along a same route or several different routes, the dominant backward blocking caused by outdated link-state information can be significantly lowered. Although parallel reservations cause some over-reservations of network capacities, the side effects are overweighed by the improvements.

Under heavy traffic loads, however, the observations are quite different. Specifically, in general mesh-topology networks, blocking performance is largely decided by the number of candidate routes rather than the number of reservations. Having more candidate routes generally leads to better performance. This is because that under heavy traffic loads, forward blocking is dominant. Therefore, having multiple candidate routes helps to increase the probability that at least one connection request could successfully reach the destination, whereas the number of reservations cannot significantly affect network performance. This conclusion also holds in ring networks, though the strong correlations reduce the significance of having two candidate routes and finally push the performance of all the schemes to be nearly the same under very high traffic loads.

From the same figure, we see that 2P-2R performs nearly the same as 1P-2R in PacNet under low traffic loads. Then 2P-2R steadily outperforms 1P-2R when overall network blocking probability is higher than 10^{-4}. In other words, within a wide range of traffic loads, having parallel reservations on different routes achieves better



(a) PacNet (b) 12-node ring

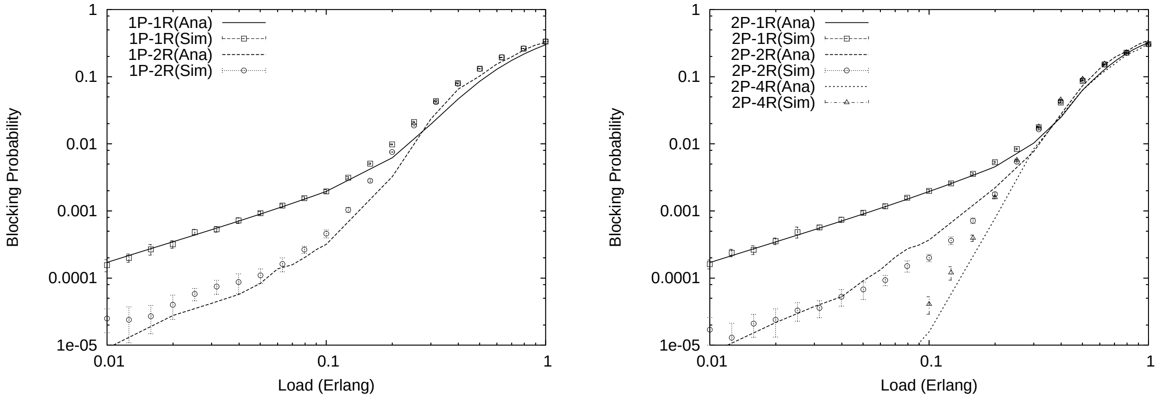
Fig. 5. Blocking performance of different parallel reservations schemes under traffic loads with an average duration of each connection of 1000 s.

performance than having them on a same route. This is because that by having multiple reservations on different routes, we have better load balance of reservation requests in the networks, which helps to avoid overloading some "hotspot" links. Such observation becomes even more obvious in ring networks, where 2P-2R always performs much better. Comparing 2P-2R and 2P-4R, we see that the latter one performs better under low traffic loads, yet slightly outperformed by the former one in the ring network under heavy traffic loads, where over-reservation effects become significant enough. Note that all the above observations apply to the case under traffic loads with an extra short average duration of connection. Only that blocking probabilities become much higher when the average duration of each connection becomes shorter, especially under light traffic loads.

Blocking performance of different schemes under traffic loads with a long average duration of connection is plot in Fig. 5. In such cases, network blocking virtually all happens in forward direction, caused by insufficient network capacities. As a result, we see that the performance is decided by the number of candidate routes rather than the number of parallel reservations: the methods with two candidate routes outperform the methods with a single route.

B. Accuracy of Proposed Analytical Model

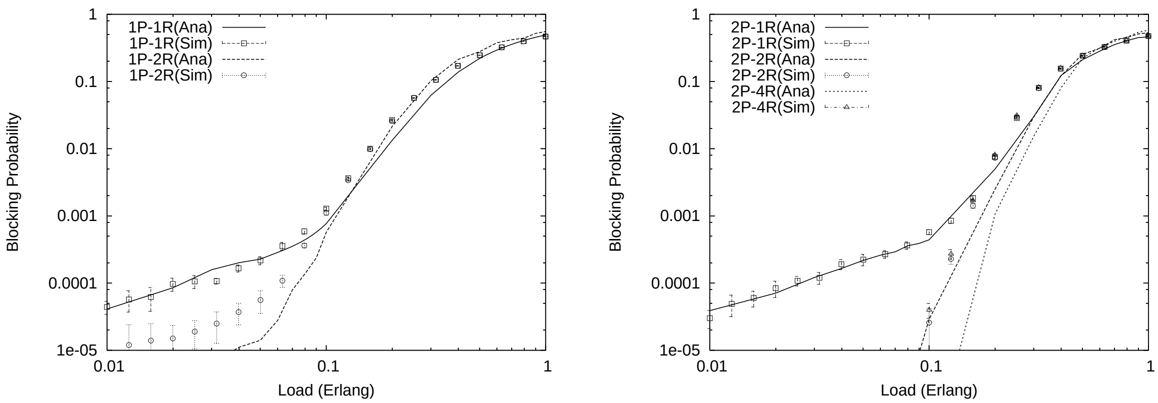
Figs. 6-10 evaluate the accuracy of the proposed models in different cases with extra short (10 ms), short (100 ms) and long (1000 s) average durations of connections, respectively. For each simulation point, we generate 10^6 connection requests and both the average and 95% confidence interval are given. To make fair comparisons, processing delay and queuing delay on each node is neglected in simulations. We see that though the proposed



(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 6. Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms.



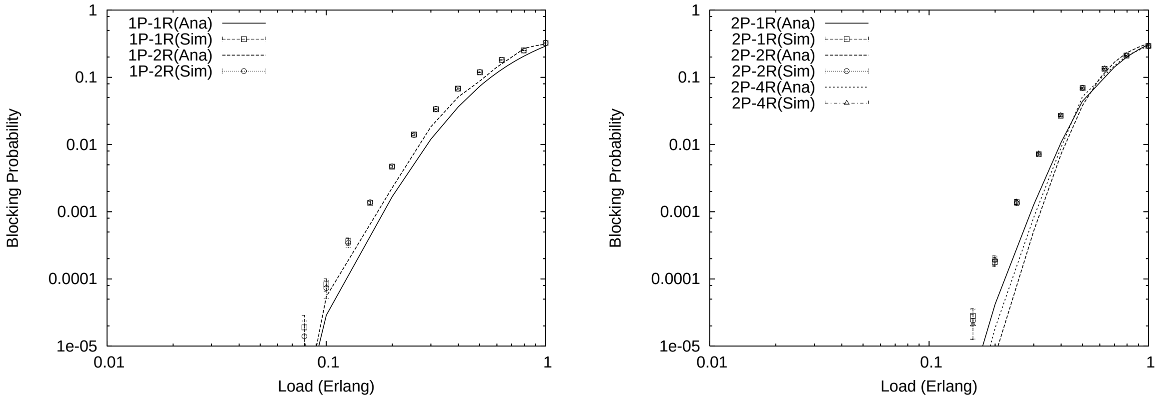
(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 7. Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms.

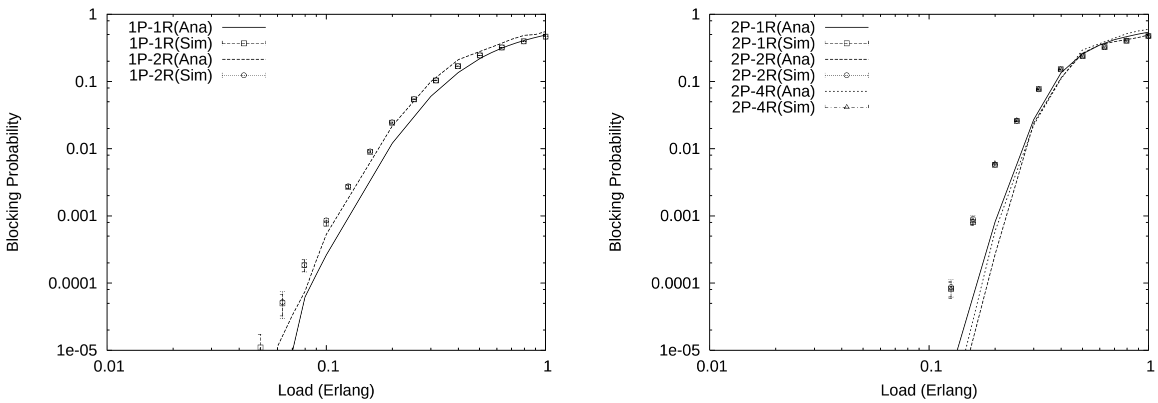
analytical models are quite general, the analysis results remain rather accurate for all the five different schemes in PacNet. In ring network where there exist strong correlations between traffic loads, accuracy of the analytical models becomes lower but basically still satisfactory.

Another interesting observation is that, when we compare the accuracy of the analytical models under short- and long-duration traffic respectively, there is no clear winner, though intuitively people may expect a lower accuracy under short-duration traffic. This can be explained as follows: the accuracy of the analytical models is mainly affected by the simplification assumptions that have been made (e.g., neighborhood-link correlation, independent attempting connections on different routes, etc.). Analysis of the cases under long-duration traffic is basically rather sensitive to these assumptions since most of the assumptions lower the accuracy of link-state calculations while link state directly decides the dominant forward blocking. Under short-duration traffic, backward blocking dominates,



(a) 1P-1R and 1P-2R (b) 2P-1R, 2P-2R, and 2P-4R

Fig. 8. Accuracy of the analytical models in PacNet under long-duration traffic with an average duration of connection of 1000 s.

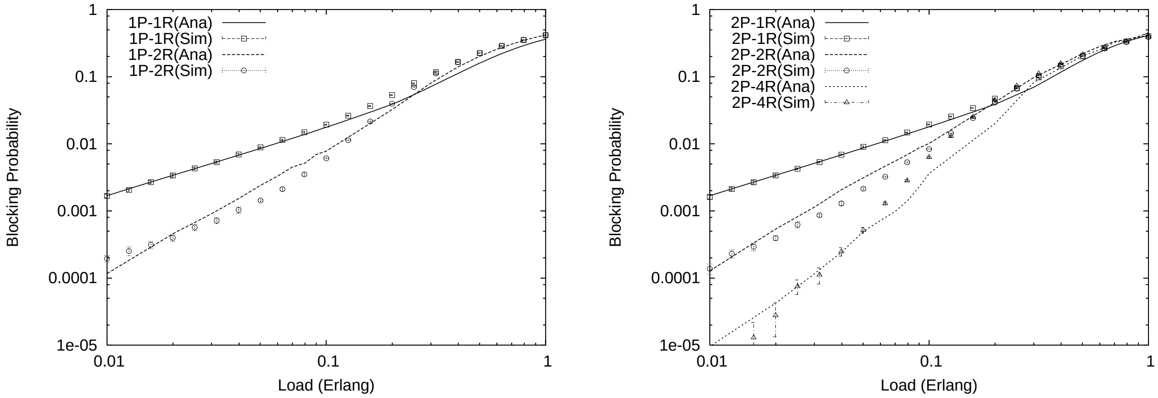


(a) 1P-1R and 1P-2R (b) 2P-1R, 2P-2R, and 2P-4R

Fig. 9. Accuracy of the analytical models in 12-node ring under long-duration traffic with an average duration of connection of 1000 s.

which to some extend is less sensitive to these assumptions since backward blocking is largely decided by the amount of outdated link-state information rather than directly by link state itself. Therefore, as long as we could correctly calculate the effects of outdated link-state information, it is actually not a surprise that a comparable, or even higher accuracy could be achieved in analyzing short-duration traffic cases.

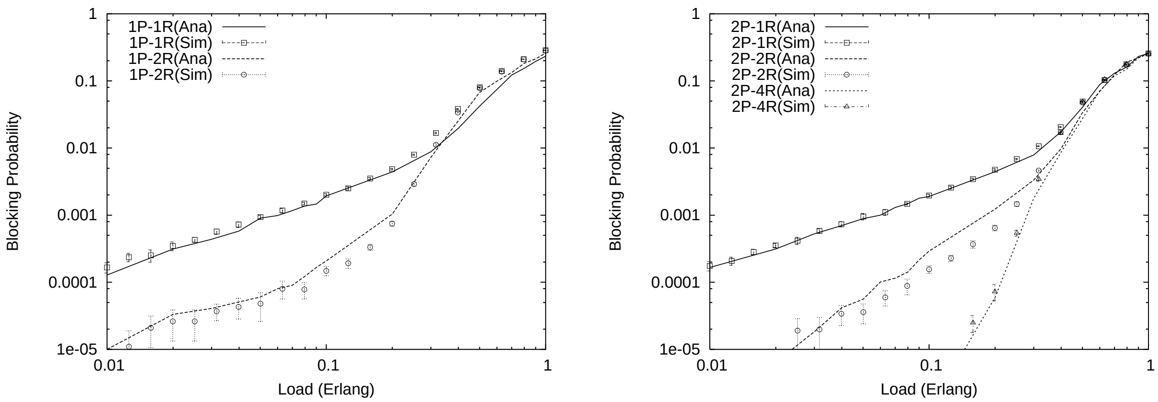
Finally, we study the case where the number of wavelength channels in each fiber is increased from 8 to 16. Simulation results in PacNet and ring network are plotted in Fig. 11 and Fig. 12, respectively. Due to limited space, only the results for the case with 100 ms average duration of connection have been presented. But the conclusions hold for all the other cases: the proposed models remain to be rather accurate; and having parallel reservations on multiple candidate routes remains to significantly improve network performance under light traffic loads.



(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 10. Accuracy of the analytical models in PacNet under extra short-duration traffic with an average duration of connection of 10 ms.



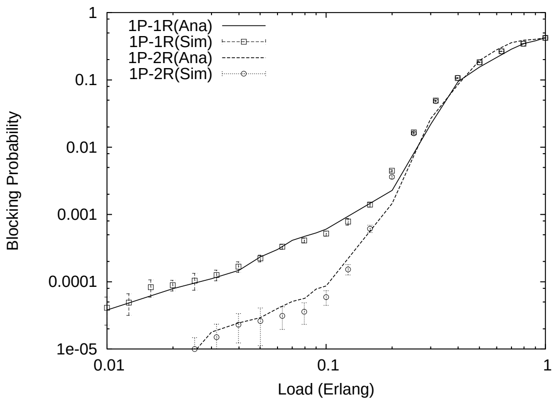
(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

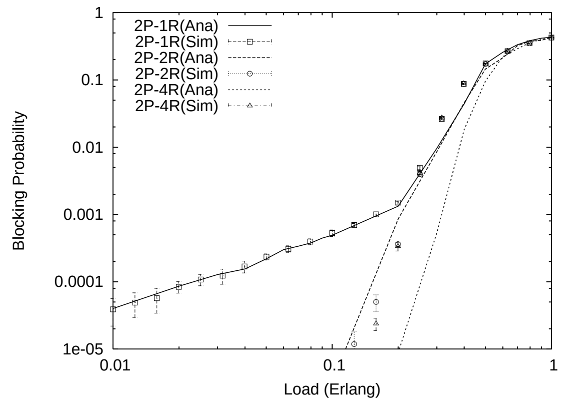
Fig. 11. Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.

C. Evaluation of Control Overhead

To measure the control overhead of the different schemes, we plot in Fig. 13 control traffic of different schemes under different data traffic loads. Specifically, whenever there is a connection/reservation/release request passing through a link, we take into account one unit of "control traffic". Since there is no standardized signaling protocol for parallel reservations, we make the exaggerative assumption that to reserve/release k $(k > 1)$ wavelengths on a same route, we need k separate reservation/release messages. Fig. 13 shows for all the five different schemes the average number of control messages generated in every second under short-duration traffic with an average duration of connection of 100ms (Control traffic is generally not a big concern under long-duration traffic). We see that though under light traffic loads, control overheads increase significantly with the increased number of candidate



(a) 1P-1R and 1P-2R



(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 12. Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.

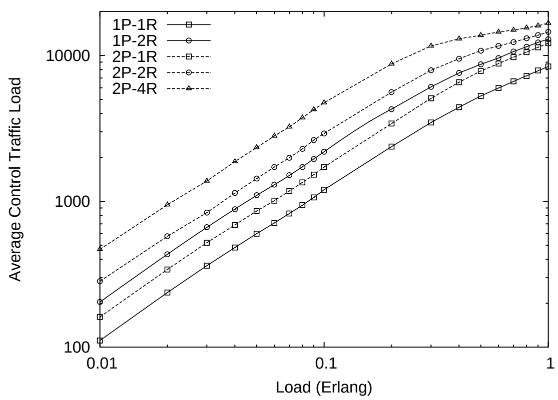


Fig. 13. The average number of control messages processed every second in PacNet under traffic with an average duration of connection of 100 ms.

routes and increased number of reservations on each route, for a well-engineered network capable of handling heavy traffic loads for the classic DIR (i.e., 1P-1R) scheme, it is reasonable to expect that the control overheads of parallel reservations are acceptable. Under heavy traffic loads, since the chance of having multiple successful reservations becomes rather low, the control traffic is not increased quite significantly compared to the classic DIR scheme. Furthermore, considering the fact that different schemes perform comparable to each other under heavy traffic loads, we expect that some new schemes could be developed to switch back to 1P-1R operation under heavy traffic loads, such that the control overheads could be further lowered.

Note that the evaluations in Fig. 13 are based on the pessimistic assumption we made above. If we assume that parallel reservations/releases on a same route could be handled by a single message, then 1P-2R has nearly the same amount of control traffic as that of 1P-1R, and 2P-4R nearly the same as that of 2P-2R. On the other hand, 2P-2R would still has a higher control overhead than that of 1P-1R. Under such case, when control overhead is a major concern, 1P-2R may be a better choice than 2P-2R, though the latter one generally leads to better network blocking performance.

V. Conclusions

In this paper we conducted a comprehensive evaluation of parallel reservation schemes for distributed lightpath establishment in wavelength-routed networks, using the MPPR scheme as a case study. We proposed a widely applicable analytical model whose accuracy has been verified by extensive simulation. Numerical results show that the parallel reservation schemes, with increased yet generally still moderate control overhead, can significantly improve network blocking performance under constantly-changing, low or medium traffic loads. We showed that parallel reservations on different routes generally perform better than making them on the same route, while too many parallel reservations may lead to serious over-reservations which actually degrade the network blocking performance.

References

[1] I. Chlamtac, A. Ganz, and G. Karmi, “Lightpath Communications: A Novel Approach to High Bandwidth Optical WANs,” *IEEE Trans. Commun.*, vol. 40, no. 7, pp. 1171–1182, July 1992.

[2] B. Mukherjee, *Optical Communication Networks*, McGrow-Hill, New York, 1997.

[3] M. Duser and P. Bayvel, “Analysis of A Dynamically Wavelength-Routed Optical Burst Switched Network Architecture,” *IEEE/OSA J. Lightwave Technol.*, vol. 20, no. 4, pp. 574–585, Apr. 2002.

[4] H. Zang, J. P. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee, “Dynamic lightpath establishment in wavelength routed WDM networks,” *IEEE Commun. Mag.*, vol. 39, no. 9, pp. 100–108, Sept. 2001.

[5] L. Berger, *et al.*, “Generalized Multi-Protocol Label Switching (GMPLS): Signaling Functional Description,” IETF, RFC 3471, Jan. 2003.

[6] R. Ramaswami and A. Segall, “Distributed Network Control for Optical networks,” *IEEE/ACM Trans. Network.*, vol. 5, no. 6, pp. 936–943, Dec. 1997.

[7] H. Zang, L. Sahasrabuddhe, J. P. Jue, S. Ramamurthy, and B. Mukherjee, “Connection Management for Wavelength-routed WDM Networks,” in *Proc. IEEE GLOBECOM’99*, vol. 2, pp. 1428–1432, Dec. 1999.

[8] Y. Mei and C. Qiao, “Efficient Distributed Control Protocols for WDM All-Optical Networks,” in *Proc. IEEE ICCCN’97*, pp. 150–153, Sept. 1997.

[9] K. Lu, G. Xiao, and I. Chlamtac, “Analysis of Blocking Probability for Distributed Lightpath Establishment in WDM Optical Networks,” *IEEE/ACM Trans. Network.*, vol. 13, no. 1, pp. 187-197, Feb. 2005.

[10] J. P. Jue and G. Xiao, “Analysis of Blocking Probability for Connection Management Schemes in Optical Networks,” in *Proc. IEEE GLOBECOM’01*, vol. 3, pp. 1546–1550, Nov. 2001.

[11] S. Shen, G. Xiao, and T. Cheng, “Benefits of Advertising Wavelength Availability in Distributed Lightpath Establishment,” *Computer Networks*, vol. 50, no. 13, pp. 2364-2379, Sept. 2006.

[12] J. P. Jue and G. Xiao, “An Adaptive Routing Algorithm for Wavelength-Routed Optical Networks with a Distributed Control Scheme,” in *Proc. IEEE ICCCN’00*, pp. 192–197, Oct. 2000.

[13] X. Masip-Bruin, *et al.*, “An Adaptive Routing Mechanism for Reducing the Routing Inaccuracy Effects in ASON,” in *Proc. ONDM’03*, pp. 333–349, Feb. 2003.

[14] K. Lu, J. P. Jue, G. Xiao, I. Chlamtac, and T. Ozuugur, “Intermediate-Node Initiated Reservation (IIR): A New Signaling Scheme for Wavelength-Routed Networks,” *IEEE J. Select. Areas Commun.*, vol. 21, no. 8, pp. 1285–1294, Oct. 2003.

[15] A. Shami, Y. Ye, C. Assi, S. Dixit, A. Hussain, and M. A. Ali, “On the Merits of Flooding/Parallel Probing-Based Signaling Algorithms for Fast Automatic Setup and Tear-Down of Paths in IP/MPLS-Over-Optical-Networks,” in *Proc. IEEE GLOBECOM’01*, vol. 4 pp. 2109–2113, Nov. 2001.

[16] A. Shami, Y. Ye, C. Assi, S. Dixit, A. Hussain, and M. A. Ali, “Multi-Path Based Distributed Routing Algorithm for WDM Routed Networks,” in *Proc. ECOC’01*, vol. 1, pp. 44–45, Sep. 2001.

[17] G. Manimaran, H. S. Rahul, and C. S. R. Murthy, “A New Distributed Route Selection Approach for Channel Establishment in Real-Time Networks,” *IEEE/ACM Trans. Network.*, vol. 7, no. 5, pp. 698–709, Oct. 1999.

[18] S. Ramamurthy and B. Mukherjee, “Survivable WDM Mesh Networks, Part II-Restoration,” in *Proc. IEEE ICC’99*, vol. 3. pp. 2023–2030, Jun. 1999.

[19] K. Lu, J. P. Jue, G. Xiao, I. Chlamtac, and T. Ozugur, “A Distributed Signaling Scheme for Provisioning Dynamic Traffic in Wavelength-Routed Networks,” in *Proc. SPIE Opticomm2003*, pp.151–162, Oct. 2003.

[20] G. Xiao and J. Liu, “Multi-Path Parallel Reservation Scheme for Distributed Lightpath Establishment in Wavelength-Routed WDM Networks,” in *Proc. ECOC’03*, vol. 3, pp. 842–843, Sept. 2003.

[21] J. Zheng, B. Zhang, and H. T. Mouftah, “Toward Automated Provisioning of Advance Reservation Service in Next-Generation Optical Internet,” *IEEE Commun. Mag.*, vol. 44, no. 12, pp. 68-74, Dec. 2006.

[22] R. Martinez *et al.*, “Challenges and Requirement for Introducing Impairment-Awareness into the Management and Control Planes for ASON/GMPLS WDM Networks,” *IEEE. Commun. Mag.*, vol. 44, no. 12, pp. 76-85, Dec. 2006.

[23] A. Birman, “Computing Approximate Blocking Probability for a Class of All-Optical Networks,” *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 852–857, June 1996.

[24] S. Subramaniam, M. Azizoglu, and A. K. Somani, “All-Optical Networks with Sparse Wavelength Conversion,” *IEEE/ACM Trans. Network.*, vol. 4, no. 4, pp. 544–557, Aug. 1996.

[25] Y. Zhu, G. N. Rouskas, and H. G. Perros, “A Path Decomposition Approach for Computing Blocking Probabilities in Wavelength-Routing Networks,” *IEEE/ACM Trans. Network.*, vol. 8, no. 6, pp. 747–762, Dec. 2000.

[26] R. A. Barry and P. A. Hamblet, “Models of Blocking Probability in All-Optical Networks with and without Wavelength Changers,” *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 858–867, June 1996.

[27] A. Sridharan and K. N. Sivarajan, “Blocking in All-Optical Networks,” *IEEE/ACM Trans. Network.*, vol. 12, no. 2, pp. 384–397, Apr. 2004.

[28] R. B. Cooper and S. Katz, “Analysis of Alternative Routing Networks with Account Taken of Nonrandomness of Overflow Traffic, ” Bell Telephone Lab., Meno., Tech. Rep., 1964.

[29] S.-P. Chung, A. Kashper, and K. W. Ross, “Computing Approximate Blocking Probabilities for Large Loss Networks with State-Dependent Routing,” *IEEE/ACM Trans. Network.*, vol. 1, no. 1, pp. 105–115, Feb. 1993.

[30] H. Harai, M. Murata, and H. Miyahara, “Performance of Alternate Routing Methods in All-Optical Switching Networks,” in *Proc., IEEE INFOCOM’97*, vol. 2, pp. 516–524, Apr. 1997.

[31] S. Ramamurthy and B. Mukherjee, “Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks,” *IEEE/ACM Trans. Network.*, vol. 10, no. 1, pp. 351–367, June 2002.

[32] J. P. Lang, V. Shama, and E. A. Varvarigos, “An Analysis of Oblivious and Adaptive Routing in Optical Networks with Wavelength Translation,” *IEEE/ACM Trans. Network.*, vol. 9, no. 4, pp. 503-517, Aug. 2001

[33] H.-Y. Jeong and S.-W. Seo, “An Approximate Analysis of Adaptive Routing in Wavelength-Routed Networks,” in *Proc. COIN-PS*, pp. 161-163, Jul. 2002.

[34] H.-Y. Jeong and S.-W. Seo, “Blocking in Wavelength-Routed Optical Networks with Heterogeneous Traffic,” *IEEE J. Select. Areas Commun.*, vol. 23. no. 8, pp. 1643-1657, Aug. 2005.

[35] A. Tucker, *Applied Combinatorics*, John Wiley & Sons Inc., 3rd ed., 1995.

[36] M. Goyal, G. Li, and J. Yates, “Shared Mesh Restoration: A Simulation Study,” in *Proc. OFC’02*, March 2002.