Computing Path Blocking Probabilities for Traffic Splitting in Optical Hybrid Switching Networks

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***Abstract*—Recent papers in the literature on hybrid optical architectures combining path and packet switching have shown that it can be a good candidate for future optical networks. However, the optimization of the traffic splitting parameters by some metrics is vital to maximize the benefit by the hybrid architecture. Blocking rate is one of the most important performance metrics in a path switching network. In this paper, we propose an analytical method to compute both forward and backward blocking rates in path switching optical WDM networks with destination-initiated reservation. On a mesh topology we show that the results of our analytical method and simulations are close to each other.**

***Index Terms*—Blocking probability, wavelength-division multiplexing, analytical model, path switching**

I. Introduction

Compared to electrical cabling, optical fiber with wavelength division multiplexing (WDM) allows much higher bandwidth and can span longer distances, so it is a promising solution to handle the fast-growing Internet traffic that is demanding more and more capacity. WDM can employ different switching granularities in order to utilize the vast capacity of fiber links e.g., packet, burst and path (circuit) switching, where each of them have pros and cons. While optical packet switching allows higher utilization of WDM channels thanks to its high statistical multiplexing gain and flexibility, it has disadvantages like higher switch cost as it needs ultra-fast switching fabric to achieve high granularity. Moreover, the current optical buffering technology is not mature enough to provide large and fast buffering space to optical packet switching. On the other hand, path switching has many advantages over packet switching like low switch cost and power requirements as its switching speed and frequency is lower. Moreover, it does not need optical buffering at the core nodes as there is no contention of packets, so it has an easier and more effective QoS support for flows with strict QoS requirements. However, path switching has lower utilization efficiency in the dedicated channel because a connection may or may not use the capacity. Moreover, path switching needs prior reservation of channels that adds an additional delay to flow completion time. A possible solution to these issues is using a hybrid-architecture combining path and packet switching to exploit the best of both worlds [1], [2]. A common approach is to carry short flows over packet switching wavelengths, while carrying the large flows on path switching wavelengths [3]. However, there are open questions like optimum ratio of path and packet-switching wavelengths and the optimum flow size threshold in order to minimize the transfer time of flows. Optimization of these parameters requires fast and easy calculation of performance metrics for path and packet-switched networks. A key performance metric in path-switched networks is the blocking probability. The maximum number of simultaneous connections on a fiber is limited, so the wavelength reservation algorithm has a big impact on the blocking the probability. One of the most popular reservation algorithms in the literature is destination-initiated reservation (DIR) [4]. In DIR, when there is a connection request, source node sends a PROBE packet, which collects a list of idle wavelengths along the path. Destination node selects one of the wavelengths, which is idle on all links in order to satisfy the wavelength-continuity constraint [5] when there is no wavelength conversion ability in the network. In case there is no idle wavelength left in the list, node sends a P_NACK packet to the source, which causes the connection request to be dropped at the source and this is called forward blocking. If the destination selects an idle wavelength, it sends a RESV packet to the source node in order to reserve it along the path. However, a previously idle wavelength may have been reserved by another connection when the reservation packet arrives. This is called backward blocking. In this case, the RESV packet is converted to R_NACK packet and reservation is no longer done in the rest of the path. If the source node receives a R_NACK packet, again it drops the connection request and sends a RELEASE packet to the destination to release the reservations done by the RESV packet. RELEASE packet may also be sent from the failed node for faster release instead of the source node, but in this work we employ the conservative method where RELEASE is sent by source nodes [6]. If the source node receives a RESV packet, it means that the selected wavelength has been reserved successfully along the path, so it sends the data over this wavelength. When the flow is finished, source node sends a RELEASE packet to remove the reservation of the reserved wavelength.

Several analytical models for calculating the forward and backward blocking rate in path switching have been proposed in the literature. Most of them are based on Reduced Load Approximation (RLA) method, which calculates the blocking rates in an iterative manner [7]. The initial analytical models in the literature were on calculating only the forward blocking due to insufficient number of channels to accept all the reservation requests. In [8] forward blocking rate is calculated by RLA method considering the state-dependent arrival rate of flows by solving an $M/M/c/c$ birth-death process. However, the analysis in [8] is for electronic circuit-switching networks, so it does not take the wavelength-continuity constraint into account. Wavelength-continuity constraint is introduced in [9] and [10] where Birman's method [9] is more advanced as it includes the state-dependent arrival of flows like in [8]. Computational complexity in Birman's method increases with the path length, so a different model based on inclusion-exclusion principle was proposed in [11] to lower the computation complexity independent of the path length. Moreover, it proposes a link correlation model to get more precise results on sparse networks. However, its authors state that this method introduces significant round-off errors if the blocking probabilities are small and wavelength count is higher than 64, so it must be used with caution when analyzing networks with large capacities at low blocking probabilities. However, a single fiber cable can carry over a thousand channels with today's WDM technology, much more than the limit stated in the paper. Ref. [12] proposes an original method that analyzes the network by decomposing it into single-path subsystems and constructing an exact Markov process that captures the behavior of a path in terms of wavelength use.

To the best of our knowledge, the first analytical model that includes the calculation of backward-blocking rate was proposed in [6]. This model calculates the forward blocking rate by considering each wavelength as an $M/G/1/1$ queuing model to obtain the stationary probability of each wavelength. However, this method does not take the state-dependent arrival rate of flows into account, so it has a higher error rate at high traffic load when compared with [9]. The backward blocking rate is calculated by incorporating the wavelength reservation duration and propagation delays in the analysis to include the blocking due to outdated information. Another analysis that includes the backward-blocking is in [13]. It calculates the forward-blocking by Birman's method [9], so the forward blocking calculation is more precise than [6]. However, the backward blocking analysis in [13] makes too many simplifying assumptions, which make it less precise than the backward blocking analysis in [6]. Ref. [14] improves the model based on inclusion-exclusion principle, which was proposed in [11]

In this paper, we used Birman's method for calculating forward blocking rates. We further improved the backward blocking analysis in [6] for more precise results and adapted to use it with Birman's method for an iterative calculation. We introduced estimation of state-dependent arrival rate of RESV packets for backward reservation, instead of using an average value like in [6]. While the models based on inclusion-exclusion principle [11] and [14] have a lower computation complexity than Birman's method, processing speed of modern CPUs is enough to solve large topologies with ease. Moreover, the inclusion-exclusion principle is limited to small number of

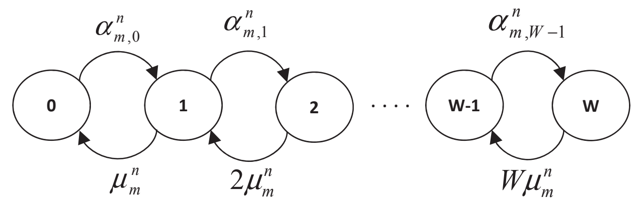

Fig. 1. Birth-death process

wavelengths, but future optical networks may carry hundreds or thousands wavelengths, so we chose Birman's method for the calculation of forward blocking.

The paper is organized as follows. In Section II, we propose an analytical model for calculating the blocking probability of DIR method. Numerical results are presented compared with simulation results in Section III. Section IV concludes the paper.

II. Analytical Model

Let W be the total number of wavelengths and k be the number of busy wavelengths on the n^{th} link of node pair m. Let $p^n_{m,k}$ be the wavelength occupancy probability, $\alpha^n_{m,k}$ be the arrival (call setup) rate, and μ^n_m be the departure rate for flows, when there are exactly k busy wavelengths on the link. The number of busy wavelengths on the link can be modeled by a birth-death process ($M/G/c/c$ queueing system, also known as Erlang loss model) as shown in Fig. 1. We assume Poisson flow arrivals, which is shown to hold on real core networks where a large number of flows are multiplexed [15]. Erlang loss model is insensitive to connection holding time distribution, so μ^n_m can be any distribution.

State probabilities can be calculated by the well-known Erlang equations

$$p^n_{m,k} = [\frac{\alpha^n_{m,0}\alpha^n_{m,1}\cdots\alpha^n_{m,k-1}}{k!(\mu^n_m)^k}]p^n_{m,0} \quad (1)$$

where

$$p^n_{m,0} = \frac{1}{1+\sum\limits_{k=1}^{W}\frac{1}{k!}\prod\limits_{j=0}^{k-1}\frac{\alpha^n_{m,j}}{\mu^n_m}} \quad (2)$$

Let $q^n_{m,k}$ be the probability that k wavelengths do not satisfy the wavelength continuity constraint along the first n hops of a node pair m with a total hop length of d, as they are busy on at least one of the hops. For the first hop, the probability is simply $q^1_{m,k} = p^1_{m,k}$. If we assume mutual independence of wavelength distribution between adjacent links, on the second hop of a path we can write

$$q^2_{m,k} = \sum_{i=0}^{W}\sum_{j=0}^{W} R(W-k|W-i, W-j)p^1_{m,i}p^2_{m,j} \quad (3)$$

where

$$R(k|i,j) = \frac{\binom{i}{k}\binom{W-i}{j-k}}{\binom{W}{j}} \quad (4)$$

if $max(0, i+j-W) \leq k \leq min(i, j)$ and is equal 0 otherwise. Eq. (4) is the conditional probability of having k wavelengths idle on both links, given that there are i idle wavelengths on the first link and j idle wavelengths on the second link. For an n-hop path we can calculate $q^n_{m,k}$ recursively by

$$q^n_{m,k} = \sum_{i=0}^{W}\sum_{j=0}^{W} R(W-k|W-i, W-j) q^{n-1}_{m,i} p^n_{m,j} \quad (5)$$

Let e_m be the departure rate of probe packets and let $\lambda^n_{m,k}$ be the arrival rate of probe packets from a node pair m to link n that are not blocked on this link (satisfying the wavelength continuity constraint) when there are k busy wavelengths on the link. If the path has a single hop, the call setup rate to the destination node simply equals to $\lambda^1_{m,k} = e_m$. In case of a multi-hop connection, the arrival rate to the destination hop depends on blocking probabilities on previous hops and the wavelength occupancy of the final link. Similar to the blocking probability calculation, call setup rate for a 2-hops path, when there are exactly k busy wavelengths on the second link, can be calculated by

$$\lambda^2_{m,k} = e_m(1 - \sum_{i=0}^{W} R(W|W-i, W-k) p^1_{m,i}) \quad (6)$$

In case of an n-hops path, we can calculate the call setup rate recursively by

$$\lambda^n_{m,k} = e_m(1 - \sum_{i=0}^{W} R(W|W-i, W-k) q^{n-1}_{m,i}) \quad (7)$$

Let γ^n_m be the average rate of call setup requests from node pair m that reserve a wavelength successfully on the link n. On the last link d of a node pair m, it is calculated by

$$\gamma^d_m = e_m(1 - q^d_{m,0}) \quad (8)$$

where $q^d_{m,0}$ is the forward blocking rate of the node pair. These successful call setup requests select an idle wavelength and try to reserve the same wavelength number along the path from destination to source node. The reader is referred to [9] for more detail on forward blocking calculations in (1-8).

Next, we calculate the rate of backward reservation requests, which are categorized into two classes;

1) Class 1: The selected wavelength is available at all the links along the path, so it will be reserved and the data transmission will occur. Let δ_m be the rate of class 1 traffic for node pair m.

2) Class 2: The selected wavelength has already been reserved at some upstream link by another node pair, so the reservation and the data transmission will fail. Let β^n_m be the rate of class 2 traffic for node pair m on link n.

First, we need to derive the probability that a selected wavelength, which was idle when the probe packet arrived, is still not reserved by other interfering node pairs, when the reserve packet arrives to that link on the backward path after some delay. For this purpose, we should know the reservation arrival rates of interfering node pairs. There may be two types of interfering reservation request arrivals on a link n. The first type of requests comes from the node pairs that will do their first reservation on this link because n is the last link on their path. The second type comes from the interfering node pairs that have the link n on their path, but n is not their last link. An important point is that if the path of two node pairs interfere at two or more links, backward reservation contention occurs only at the first interfering link n, which is the one closest to the destination. Therefore, there should be no contention at links $n + c$, where $c > 0$. The original backward blocking model in [6] does not take this into account, but we improved the model to handle this situation. Let $\gamma^n_{m,k}$ be the rate of call setup requests from a node pair m, which reserve a wavelength successfully on the link n, when there are k busy wavelengths on the link. Let m_n be the link id of the n^{th} link of node pair m in the overall topology, M be the set of all node pairs in the network and $d(m)$ be the hop count of node pair m. Let $\Lambda^n_{m,k}$ be the total arrival rate of reservation requests of node pairs interfering with requests from node pair m, when there are k busy wavelengths on link n. As a result, $\Lambda^n_{m,k}$ can be calculated by

$$\Lambda^n_{m,k} = \sum_{\substack{m' \in M,\\ m'_{n'} = m_n,\\ n' = d(m')}} \lambda^{n'}_{m',k} + \sum_{\substack{m' \in M,\\ m' \neq m,\\ m'_{n'} = m_n,\\ m'_{n'+c'} \neq m_{n+c},\\ n' \neq d(m')}} \gamma^{n'}_{m',k} \quad (9)$$

for the first $d - 1$ links of node pair m, where the value of λ and γ variables come from the previous iteration of the algorithm. This interfering traffic causes backward blocking, which decreases the arrival rate of reservation requests of a node pair at each interfering hop on the way to the source node.

Let D be the two-way propagation delay of a link. We show it as a constant to simplify the notations, but it is possible to calculate with different link delays in the network. Assuming that interfering traffic arrival is Poisson, we can estimate the arrival rate of reservation requests from node pair m that succeed in reservation on link $n - 1$ when there are k wavelengths on the link $n - 1$ by

$$\gamma^{n-1}_{m,k} = \gamma^n_m e^{-\Lambda^{n-1}_{m,k}(d-n+1)D/(W-k)} \quad (10)$$

As a result, the average reservation arrival rate from node pair m can be calculated by normalizing the state dependent arrival rates with the state probabilities by

$$\gamma^{n-1}_m = \gamma^n_m \sum_{j=0}^{W-1} p^{n-1}_{m,j} e^{-\Lambda^{n-1}_{m,j}(d-n+1)D/(W-j)} \quad (11)$$

Ref. [6] uses an expected wavelength occupancy ratio for calculating the reservation arrival rates. However, our

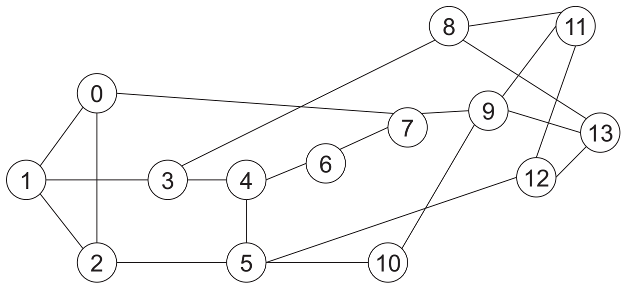

Fig. 2. NSFNET topology

model greatly improves calculation of backward blocking by estimating a specific reservation arrival rate for all possible wavelength occupancy ratios by (9-11).

As a result of (11), class 1 traffic can be calculated for all links on the path by

$$\delta_m = \gamma_m^d \prod_{x=2}^{d} \sum_{j=0}^{W-1} p_{m,j}^{x-1} e^{-\Lambda_{m,j}^{x-1}(d-x+1)D/(W-j)} \tag{12}$$

Arrival rate of class 2 traffic is simply

$$\beta_m^n = \gamma_m^n - \delta_m \tag{13}$$

Let s_m^n and t_m^n be the mean occupation times for class 1 and 2 traffic on the n^{th} link of the path of node pair m. Let φ be the mean occupation time of data transfer. Class 1 mean occupation time is

$$s_m^n = nD + \varphi \tag{14}$$

Class 2 mean occupation time is

$$t_m^n = \begin{cases} nD & \text{if n}\geq 2 \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

The mean wavelength occupation time is

$$\mu_m^n = \frac{\sum\limits_{\substack{m'\in M,\\ m'_{n'}=m_n}} \gamma_{m'}^{n'}}{\sum\limits_{\substack{m'\in M,\\ m'_{n'}=m_n}} (\delta_{m'} s_{m'}^{n'} + \beta_{m'}^{n'} t_{m'}^{n'})} \tag{16}$$

The overall arrival rate when there are k busy wavelengths on the n^{th} link is calculated similar to (9) by,

$$\alpha_{m,k}^n = \sum_{\substack{m'\in M,\\ m'_{n'}=m_n,\\ n'=d(m')}} \lambda_{m',k}^{n'} + \sum_{\substack{m'\in M,\\ m'_{n'}=m_n,\\ n'\neq d(m')}} \gamma_{m',k}^{n'} \tag{17}$$

Finally, the blocking probability of a node pair m with hop count d is

$$L_m = 1 - (1 - q_{m,0}^d) \prod_{x=2}^{d} \sum_{j=0}^{W-1} p_{m,j}^{x-1} e^{-\Lambda_{m,j}^{x-1}(d-x+1)D/(W-j)} \tag{18}$$

We used the following algorithm to employ these equations to calculate blocking probability by RLA method, iteratively.

1) Initialize L_m for all the node pairs to zero. Initiate state dependent arrival rates as if there is no blocking in the network.

2) Calculate the wavelength occupation time μ_m^n

3) Calculate the state-dependent arrival rate $\alpha_{m,k}^n$

4) Derive the new blocking probability L_m. If the difference between the old and new value of L_m for each node pair is less than small constant (we used 10^{-7} in this paper), then finish the iteration. Otherwise, return to step 2 and begin the next iteration.

III. Numerical Results

We evaluate the performance of the analytical method on the NSFNET with 14 nodes and 21 bidirectional links shown in Fig. 2. Each link carries 16 wavelengths in both directions. The link propagation delay is 10 ms. Flow holding time has a mean value of 0.1 seconds. Erlang loss model is insensitive to connection holding time distribution. However, we apply an exponential holding time distribution for easier and faster simulation. We apply the traffic demand matrix in [16] with shortest-path routing. Flows between each node pair arrive according to a Poisson process. Blocked connection attempts are dropped without retrying. Total number of flows in the simulation was 4×10^9, where first 4×10^8 flows were discarded from the results.

Many works in the literature report only the overall blocking rate in the network as a result, but the overall rate may be misleading because analytical and simulation results of individual source-destination (s-d) pairs may have high deviation while giving a close result when the network-wide average is calculated. Therefore, we report the results of all s-d pairs for greater insight. Fig. 3 plots the analytical and simulation results sorted in descending order by simulation result of blocking rate for each s-d pair in the network. X-axis shows the s-d pair index. There are 181 s-d pairs in the network. Y-axis shows the average blocking rate where 1 means 100% blocking. Analytical result by the model proposed in [6] is included in the figure for comparison. The reservation protocol in [6] has a small difference causing $0.5D$ difference in reservation time calculations. We converted it to our reservation time calculation method for a fair comparison. Fig. 3 shows the results when total reservation request arrival rate in the network is 400 requests/second. Fig. 3(a) shows the blocking rate in a linear scale. Small blocking probabilities are difficult to see in the linear scale, so we plotted the same graph in log scale in Fig. 3(b). We see that the result of our analytical calculation is almost the same as the simulation result. However, the analysis by [6] has a high error rate.

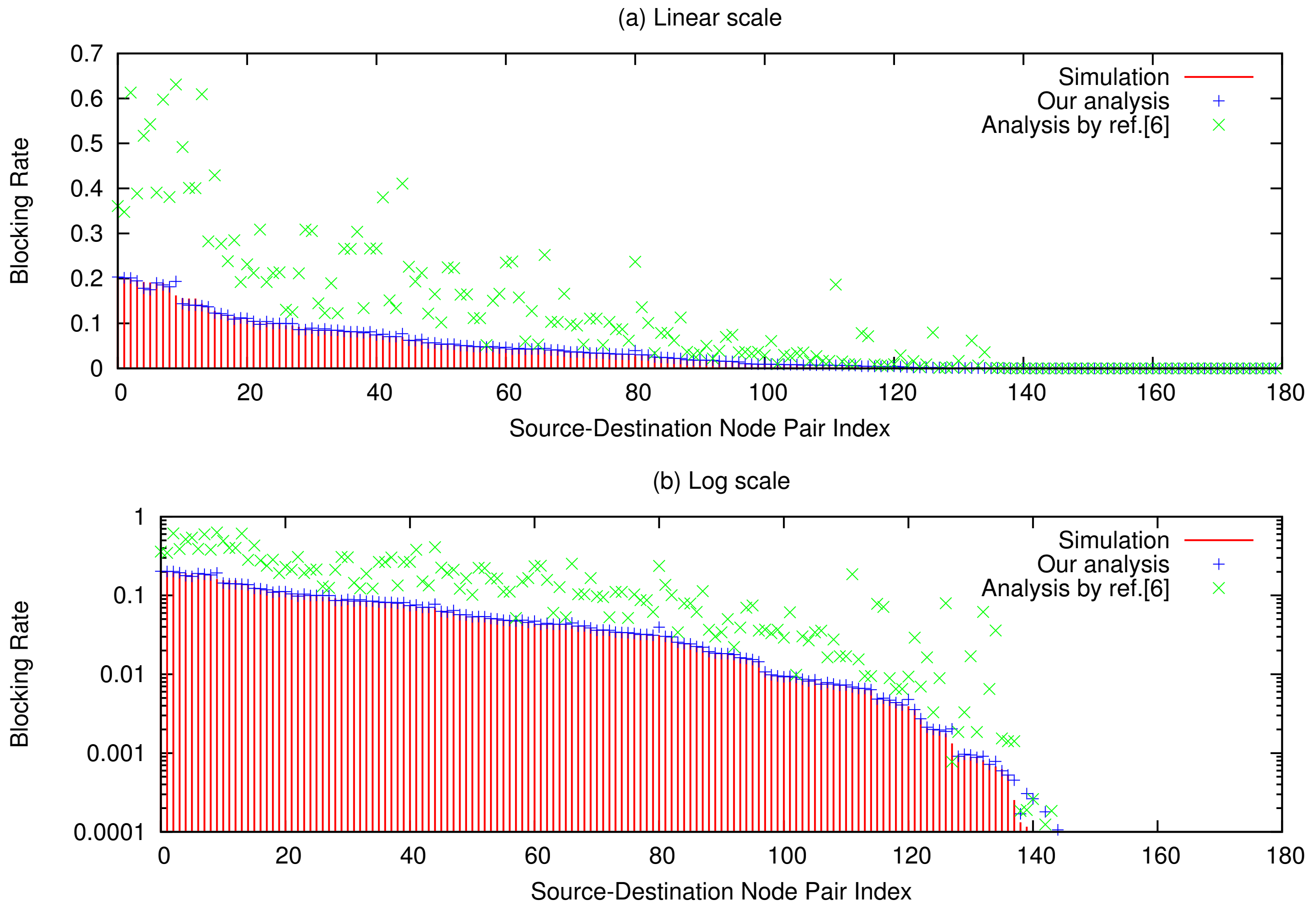

Fig. 3. Comparison of analytical and simulation results when the total reservation request arrival rate in the network is 400 requests/second.

Most of the analytical methods in literature have problems when estimating the blocking rate on highly loaded links. Fortunately, most core networks on the Internet are operated at low loads, but we also present a high load example in Fig. 4 as a worst case scenario by increasing the total reservation arrival rate to 2000 requests/second. This causes over 95% blocking ratio on some links. Comparison of the two analytical methods reveals that the result of our analysis is much closer to the simulation results than the model in [6] even on a heavily congested network.

The analytical calculation of our result in Fig. 4 took around 7 seconds on a single core of Intel X5365 CPU released in 2007, by a not so optimized single-threaded program written in C++. It seems possible to compute the same analytical result in less than 0.1 seconds by a well-optimized, multi-threaded program on a recent multi-core CPU.

IV. Conclusions

In this paper we proposed an analytical method based on reduced load approximation for calculating blocking probabilities in path switching optical WDM networks with destination-initiated reservation. Such an analytical method can be very useful in fast calculation of blocking probability for traffic engineering and optimization of the traffic splitting parameters for hybrid optical architectures combining path and packet switching. We compared the analytical and simulation results on a mesh NSFNET network and showed that their results are close to each other.

As a future work, we will try to increase the accuracy of forward blocking calculation and extend the analytical model to incorporate the retrial of blocked connections.

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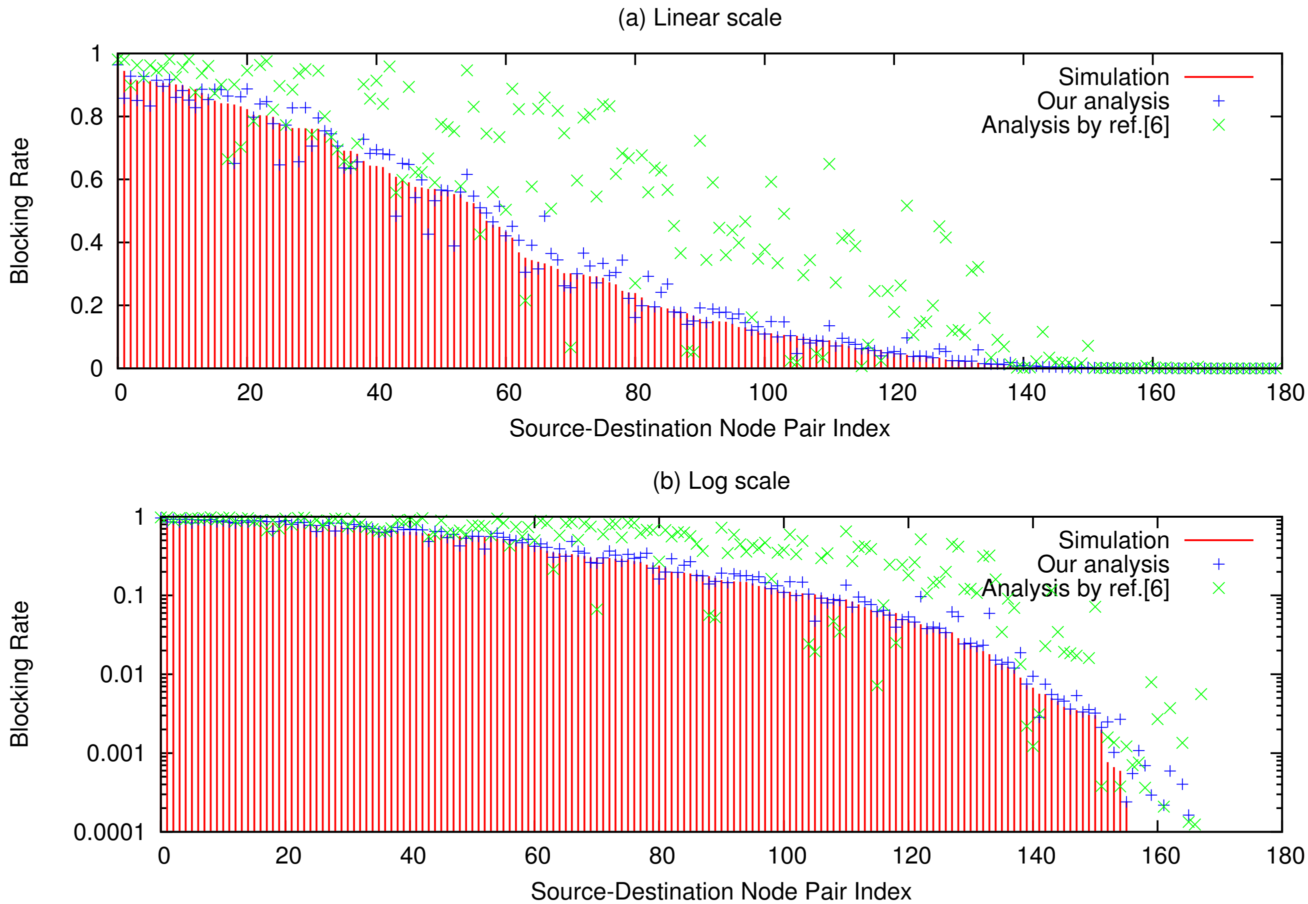

Fig. 4. Comparison of analytical and simulation results when the total reservation request arrival rate in the network is 2000 requests/second

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