Performance Analyses of Wavelength Reservation Methods for High–Speed Data Transfer in Photonic Networks

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Abstract: It is possible to offer a high speed data transfer capability by employing a WDM technology. One promising method is to transfer the data through a fast wavelength assignment. However, the wavelength reservation time, including the propagation delay between source and receiver nodes, becomes large, which may lead to performance degradation. In this paper, we develop a new approximate analytical method, which incorporates wavelength reservation times. We consider two methods for wavelength reservation; a forward method in which wavelength assignment is performed along the forward path from source to receiver, and a backward method in which it is performed along the backward path. Based on our approximate analysis, we investigate the effects of propagation delays on both methods.

1. Introduction

An exponential growth of the Internet traffic has led to the capacity demand for the backbone networks. A most promising solution seems to use a WDM (Wavelength Division Multiplexing) technology. For effectively utilizing WDM, we consider the fast wavelength assignment method on demand basis in this paper. That is, when the data transfer request arises, the wavelength is dynamically assigned between source and destination nodes, and the data is transfered using the assigned wavelength. The wavelength is immediately released when the data transfer is successfully finished. In such a method, the influence of wavelength assignment time, including the propagation delay between the source and destination, becomes a key issue to achieve a high throughput such that the large bandwidth provided by the WDM technology can be enjoyed. However, a lot of papers so far have ignored the influence as in [1, 2] except [3, 4].

In [3, 4], the authors proposed several methods for wavelength reservation. Those include the forward reservation method and the backward reservation, where wavelength assignment is performed along the forward direction and the backward direction, respectively. Those methods are compared through computer simulation. Following [3], we also consider the above–mentioned two methods (see Fig. 1); In the first one, wavelength search and assignment is performed along the forward path from source to destination. If the available wavelength is found on the forward path, the information is returned from the destination node to the source node so that the source node can start the data transfer using the notified wavelength. In the second one, on the other hand, assignment is made in the opposite direction; i.e., the wavelength assignment is performed along the backward path. In what follows, we will call these two methods as RFP (*Reservation along the Forward Path*) and RBP (*Reservation along the Backward Path*) protocols, respectively. In this paper, a variant of the RBP protocol is also considered, which we will refer to as RBPD (*Reservation along the Backward Path with Dropping*) protocol. RBPD is different from RBP in that the optical node plays an active role in signaling. See the next section for more detailed description of protocols.

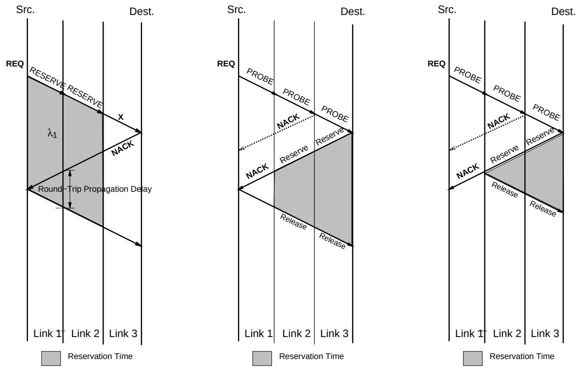
To evaluate the above three protocols, we newly develop the approximate analysis method. Our approach is based on the Reduced Load Approximation (RLA) method which is often used in analyzing the circuit–switched network. To apply the RLA method, however, we need to take account of the wavelength continuity condition in the photonic network. That is, we assume that the photonic network consists of wavelength inconvertible nodes only, and the same wavelength should be reserved between source and destination. Thus, we cannot directly apply the conventional RLA method. Further, effects of the wavelength reservation time should be considered since it much affects the performance of our network. We therefore extend the RLA method to derive the blocking probability, which is the probability that the reservation request of the source node is rejected by the network due to the lack of the available wavelength. Since the space is limited, we do not present the result, but by utilizing the blocking probability, we can easily obtain the burst data transfer delay, which is defined as the time from when the data transfer request arrives at the source node to when the data is successfully received by the destination node.

The rest of the paper is organized as follows. In Section 2., we present a brief description of the protocols we will investigate. We then present our approximate analysis in Section 3.. In Section 4., we assess the accuracy of our approximate analysis and give some numerical discussions. In Section 5., we conclude our paper.

2. Wavelength Reservation Protocols

In this section, we briefly illustrate three protocols. At the time when the source node has data to transmit, the reservation request is forwarded along the predefined path. In the RFP protocol, the list of available wavelengths is passed from the source node to the destination node. Each intermediate node along the forward path removes wavelengths from the list if those wavelengths are currently used by other requests. At the same time, the available wavelengths in the list are reserved. If the intermediate node finds that the list has no available wavelengths, it returns the NACK signal to the source node. When the destination node receives the list, it selects one wavelength from the list and notifies of the source node so that the source node can transfer the data on the chosen wavelength. When the intermediate node detects the data tranmission, it releases the wavelengths which were temporarily reserved but not selected.

In the RBP protocol, on the other hand, only the information on usage of the wavelengths is collected along the forward path, and the wavelength reservation is not made at this time. Each intermediate node on the forward path only removes the wavelengths from the list if those wavelengths are currently used. If the list contains no wavelengths, then the node returns the NACK signal to the source node directly. When the list of the available wavelengths is returned to the source node by the destination, each intermediate node actually makes wavelength reservation. When the source node finally receives the list, one wavelength is selected from the list. The wavelengths temporarily reserved at each node but not used for data transfer are released as the data is actually transmitted. If the wavelength is not available, on the other hand, the source node propagates the release signal (to show that the wavelength assignment fails) along the forward path.



(a) RFP (b) RBP (c) RBPD

Figure 1: Example behaviors of three protocols

In this paper, a variant of the RBP protocol is also considered, which we call a RBPD (*Reservation along the Backward Path with Dropping*) protocol. Different from the RBP protocol, the intermediate nodes actively propagate the NACK signal to the downstream nodes in the RBPD protocol, by which the faster release of the reserved wavelength can be expected. A quantitative evaluation will be given in Section 4..

In all of the above protocols, the source node tries the reservation request later if the wavelength assignment fails due to lack of available wavelengths. This process is repeated until the wavelength assignment succeeds.

3. Analysis

3.1 Network Model and Assumptions

We introduce the following notations and assumptions.

(1) The number of links within the network is J, and each link has the number W of wavelengths. The wavelengths are represented as λ_1, λ_2, ..., λ_W.

(2) The route for every node pair a, R_a, is assumed to be fixed. The number of hops of route R_a is represented by h_a. Thus the link set along route R_a from the source node is $\{a_1, a_2, \ldots, a_{h_a}\}$.

(3) $D^{(j)}$ denotes two-way propagation delay of link j. In this paper, we assume that $D^{(j)} \equiv D$ for every link j.

(4) Let $m_w^{(j)}$ represent the availability status of the wavelength λ_w on link j. If wavelength λ_w is used for transmitting the data or reserved by some node pair, $m_w^{(j)} = 0$, otherwise $m_w^{(j)} = 1$.

(5) The arrivals of data transfer requests at every node pair a are assumed to be governed by a stationary Poisson process with parameter e_a. The analysis itself does not limit the homogeneous arrivals, but we assume it for simplicity. The data transfer time for each request is assumed to be exponentially distributed with mean $1/\mu_a$. Note that it does not include the propagation delays.

(6) Each link prepares a channel for control signals.

(7) The processing delay at the node is assumed to be negligible for simplicity. However, it is possible to be incorporated in the propagation delay in our approximate analysis.

3.2 Analysis Approach

Let the steady state probability that the wavelength λ_w is available on link j be $q_w^{(j)}(m_w^{(j)})$, $m_w^{(j)} = 0, 1$. By assuming that the wavelength for data transfer is randomly selected from the available wavelengths, steady state probabilities of availabilities on wavelengths at each link are identical, i.e.,

$$q_1^{(j)}(m) = q_2^{(j)}(m) = \ldots = q_W^{(j)}(m), \quad m = 0 \text{ or } 1.$$

Thus, we will use $q^{(j)}(m)$ instead of $q_w^{(j)}(m)$ in the below. We further introduce the assumption that each node behaves independently following the RLA method. That is, steady state probabilities $\{q^{(j)}(m)\}$ can be determined regardless of the states of other nodes.

The wavelength on each link is modeled by a queueing system as follows. The arrival of data transfer requests to each wavelength on link j is governed by a Poisson process with parameter $\Lambda^{(j)}$ when the wavelength is available. While we have assumed that the data length follows the exponential distribution, it does not directly mean that the service time is given by the data transfer time at the link. It is because we need to take account of the reservation time of the wavelength as a part of the service time received at the node. The reservation time is dependent on the position of the node on the path (forward path in the case of RFP and backward path in RBP and RBPD). Further, the reservation may be rejected by another node if the wavelength is not available at that node. In the latter case, the service time at the link is only determined by the propagation delays since the data transfer is not performed. For example, if we consider the RFP protocol, node i reserves the wavelengths when it receives the reservation request. However, the reserved wavelengths may be rejected by the other downstream node, and the reserved wavelength is released when the notification arrives at node i. It takes two–way propagation delays between node i and the destination node by our definition.

Thus, we need to consider the various times (including the wavelength reservation time and possibly actual data transfer time) to model the service time at the link. Hereafter, we call it as *wavelength occupation time* during which the wavelength is not available to other requests. We therefore model the wavelength on the link as the queueing system where the jobs (data transfer requests) arrive with the general service time with mean $1/T^{(j)}$ (we omit the wavelength index since wavelengths on the link can be treated identical). Its derivation will be described in the next subsection.

By modeling each wavelength at the node as an M/G/1/1 queuing model, we can obtain the stationary probability of each wavelength at link j as

$$q^{(j)}(0) + q^{(j)}(1) = 1, \;\; \Lambda^{(j)} q^{(j)}(1) = T^{(j)} q^{(j)}(0).$$

It follows that

$$q^{(j)}(0) = \frac{\Lambda^{(j)}}{\Lambda^{(j)} + T^{(j)}}, \; q^{(j)}(1) = \frac{T^{(j)}}{\Lambda^{(j)} + T^{(j)}}. \qquad (1)$$

From Eq. (1), we can determine the steady state probabilities once we know $\Lambda^{(j)}$ and $T^{(j)}$ (see the next subsection for derivation). For this purpose, we extend a *Reduced Load Approximation* method often used in circuit-switched networks. L_a, the blocking probability of the data transfer requests can then be determined as will be described in Subsection 3.4.

The outline of our numerical algorithm is as follows.

(i) Initialize L_a for all the node pairs $\{a\}$, steady state probabilities $q^{(j)}(1)$, $q^{(j)}(0)$. In the numerical examples, we will use $L_a = 1$, $q^{(j)}(1) = 1$ and $q^{(j)}(0) = 0$.

(ii) Calculate the arrival rate for the wavelength $\Lambda^{(j)}$ $(j = 1, \cdots, J)$ (see Subsection 3.3).

(iii) Calculate the wavelength occupation time $1/T^{(j)}$ $(j = 1, \cdots, J)$ (see also Subsection 3.3).

(iv) Calculate the steady state probabilities $\{q^{(j)}(m)\}$'s from Eq. (1).

(v) Derive the new blocking probability L_a (see Subsection 3.4). If new values of L_a are acceptably close to old ones, then finish the iteration. Otherwise, return to Step.(ii) to begin next iteration. We will use the relative value of 10^{-6} to obtain the numerical results shown in Section 4..

3.3 Determinations of $\Lambda^{(j)}$ and $T^{(j)}$

In what follows, we only describe the RBP protocol. The cases of the RFP and RBPD protocols are omitted due to space limitation, but can be analyzed in a similar way to the RBP protocol.

Request arrivals at i–th link for node pair a are categorized into the next two classes;

- Class 1: The requests which will be eventually accepted because the wavelength is available at all the links along the path for the node pair.
- Class 2: The requests which will be rejected since a wavelength is already reserved or used at some upstream link(s). Recall that the actual reservation is made along the backward path in the RBP protocol.

Let the arrival rate at i–th link for node pair a be $\gamma^{(a_i)}$, and be $\alpha^{(a_i)}$, $\beta^{(a_i)}$ for Classes 1 and 2, respectively. That is,

$$\gamma^{(a_i)} = \alpha^{(a_i)} + \beta^{(a_i)}. \qquad (2)$$

The probability that a certain wavelength is available on all the links along the node pair a is given by $\prod_{i=1}^{h_a} q^{(a_i)}(1)$. By excluding that NACK is returned to the source node from the intermediate node due to lack of the available wavelength, the arrival rate of the data transfer requests at the destination is represented as

$$\sigma_a = e_a \left[1 - \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1) \right)^W \right].$$

Let σ_{select} be the probability that a certain wavelength that we consider is selected among the available wavelength. Recalling that in the RBP protocol, the destination node chooses one wavelength randomly from the list, it can be represented as

$$\sigma_{select} = \sum_{k=0}^{W-1} (k+1) \cdot \binom{W-1}{k} \left(\prod_{i=1}^{h_a} q^{(a_i)}(1) \right)^{(k)} \times \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1) \right)^{(W-k-1)}.$$

We thus have the arrival rate of reservation requests per wavelength at the final link a_{h_a}, $\gamma^{(a_{h_a})}$, as

$$\gamma^{(a_{h_a})} = \sigma_a \cdot \sigma_{select}.$$

The requests arriving at the final link are returned to the source node along the backward path. However, those requests may be rejected on some link if another request reserves the wavelength before the reservation request is returned. It is because in the RBP protocol, actual reservation is made on the backward path. That is, we need to derive the probability that on the forward path, the wavelength is available, and that on the backward path, that wavelength is still not reserved by other requests. By assuming a Poisson arrival of reservation requests, a corresponding probability can be determined as $e^{-\Lambda^{(a_k)}(h_a - k + \frac{1}{2}) \cdot D}$ on link a_{h_k}. By collecting those probabilities for links $a_{h_a - 1}$ through a_{h_1}, we obtain the arrival rates of wavelength reservation requests for Class 1 as

$$\alpha^{(a_{h_a})} = \gamma^{(a_{h_a})} \prod_{k=1}^{h_a - 1} [e^{-\Lambda^{(a_k)}(h_a - k + \frac{1}{2}) \cdot D}]. \qquad (3)$$

Class 2 traffic is then given from Eq. (2) as

$$\beta^{(a_{h_a})} = \gamma^{(a_{h_a})} - \alpha^{(a_{h_a})}.$$

Similarly, we have at link a_i $(1 \le i \le h_a - 1)$,

$$\begin{aligned} \gamma^{(a_i)} &= \gamma^{(a_{i+1})} e^{-\Lambda^{(a_{i+1})}(h_a - i + \frac{1}{2})D} \\ \alpha^{(a_i)} &= \gamma^{(a_i)} \prod_{k=1}^{i-1} [e^{-\Lambda^{(a_k)}(h_a - k + \frac{1}{2}) \cdot D}] \\ \beta^{(a_i)} &= \gamma^{(a_i)} - \alpha^{(a_i)}. \end{aligned}$$

We finally have the arrival rate to request one of wavelengths on link j as

$$\Lambda^{(j)} = \sum_{a_i = j} \gamma^{(a_i)},$$

which gives the arrival rate of requests on link j (including those eventually failing to wavelength reservation). Note that $\Lambda^{(j)}$'s are not known a priori while those are included in Eq. (3). It indicates that we need an iteration algorithm for the analysis as having been outlined in the previous subsection.

We next consider the wavelength occupation time. It is started at the time when the reservation request arrives at the node on the forward path. As before, we consider two cases separately. For Class 1 traffic, the wavelength is released when the data transfer is finished. Its mean is denoted as $s^{(a_i)}$ for link i. For Class 2 traffic, on the other hand, the wavelength temporarily reserved for possible future use is released when NACK signal is passed, and is not used for data transfer. We use $t^{(a_i)}$ to represent its mean.

In the RBP protocol, we simply have the mean occupation times for Classes 1 and 2 as

$$s^{(a_i)} = iD - \frac{D}{2} + \frac{1}{\mu_a}; \quad t^{(a_i)} = iD - \frac{D}{2}.$$

The mean wavelength occupation time, $1/T^{(j)}$, is finally determined as

$$\frac{1}{T^{(j)}} = \frac{\sum_{a_i=j}(\alpha^{(a_i)}s^{(a_i)} + \beta^{(a_i)}t^{(a_i)})}{\sum_{a_i=j}\gamma^{(a_i)}}.$$

3.4 Derivation of Blocking Probability

Recall that the probability that the available wavelength is found at the destination, $S_{bwd}^{(a)}$, is given by

$$S_{bwd}^{(a)} = 1 - \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^W. \tag{4}$$

Then, since the probability that the wavelength is still available at link k on the backward path is $e^{-\Lambda^{(a_k)}(h_a-k+\frac{1}{2})\cdot D}$, the probability that the source node successfully receives the reservation acceptance is given by

$$\prod_{k=1}^{h_a}[e^{-\Lambda^{(a_k)}(h_a-k+\frac{1}{2})\cdot D}]. \tag{5}$$

Therefore, the blocking probability L_a is derived as follows.

$$L_a = 1 - S_{bwd}^{(a)} \cdot \prod_{k=1}^{h_a} e^{-\Lambda^{(a_k)}(h_a-k+\frac{1}{2})D}. \tag{6}$$

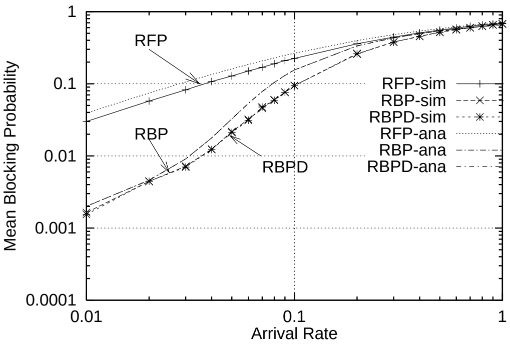
The throughput for given node–pair a is simply given by

$$(1 - L_a)e_a. \tag{7}$$

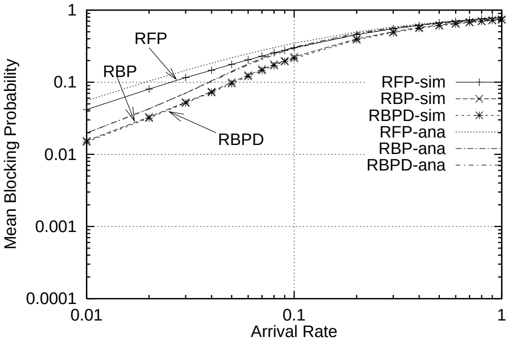
4. Performance Results and Discussions

In this section, we compare three protocols in terms of blocking probabilities based on our approximate analysis. We examine 16-node mesh-torus network as the network topology. We assume that the mean arrival rate of burst transfer request and the mean burst transmission time are identically set to $e = e_a$ and $1/\mu = 1/\mu_a$ for all the node pair a, respectively. The shortest path is used as a preassigned route for each node pair.

Due to space limit, we only show one example of comparative results. Figure 2 compares the blocking probabilities dependent on the arrival rate of the burst transfer requests are shown. We set the number of wavelength per link is 5. In Figs. 2(a) and 2(a), two cases of propagation delays D (normalized by the mean burst transmission time) are shown; $D = 0.02$ and $D = 0.2$, respectively. In the figures, the computer simulation results are also shown to assess the accuracies of our analysis results. From the figures, we can observe that RBP/RBPD protocols outperform the RFP protocol. It is because the RFP protocol tries to reserve a certain wavelength on the forward path, and therefore, it introduces the larger wavelength occupation time. On the other hand, RBP/RBPD protocols can improve the performance as Fig. 1 has indicated. When comparing RBP and RBPD protocols, the performance of RBPD protocol is better than the RBP protocol as the propagation delays become large, but it is very limited. Thus, we may conclude that the more complicated task required by the RBPD protocol is not necessary.



(a) $D = 0.02, W = 5$



(b) $D = 0.2, W = 5$

Figure 2: Performance comparisons of three protocols

5. Conclusion Remarks

In this paper, we have developed a new approximate analytical method in order to evaluate wavelength reservation protocols suitable for high speed burst data transfer in photonic networks.. We have compared performances of RFP, RBP and RBPD protocols exploiting the analysis method. The results have shown that the backward reservation protocol significantly improve the performance than RFP protocol. However, the effect of introducing the backward notification is very limited. We will extend our approximate analytical method to incorporate the retrial request when the wavelength reservation request is blocked.

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