Delay Analyses of Wavelength Reservation Methods for High–Speed Burst 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 reservation. 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 reservation 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 reservation method on demand basis. That is, when the burst transfer request arises at the source node, the wavelength is dynamically assigned between source and destination nodes, and the burst is transferred using the assigned wavelength. Here, the burst corresponds to the upper–layer protocol data unit such as the file or block in the case of file transfer. 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, 5].

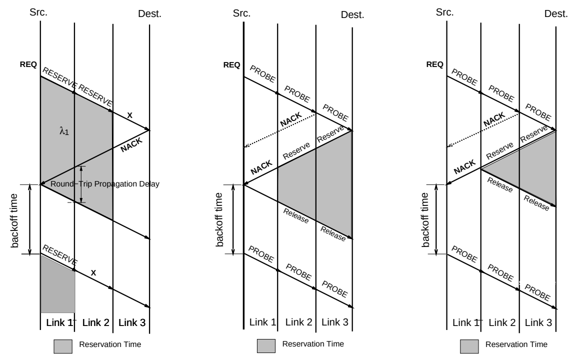
In [3, 4], the authors proposed several methods for wavelength reservation. Those include the forward reservation method and the backward reservation, where wavelength reservation is performed along the forward direction and the backward direction, respectively. Those methods are compared through computer simulation. Following [3], an approximate analysis method has been developed in [5], where the authors treat the three protocols. See the next section for detailed descriptions of protocols. For three protocols, the authors derived the blocking probability, which is defined as the probability that the reservation request of the source node is rejected by the network due to the lack of the available wavelength. However, a more important measure for the data transfer is 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. In this paper, by utilizing the result of [5], we analyze burst data transfer delay in the above–mentioned three protocols.

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 results. 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 burst to transmit, the reservation request is forwarded along the predefined path. In the RFP (*Reservation along the Forward Path*) 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 burst on the chosen wavelength. Each intermediate node releases the wavelengths which are temporarily reserved but not selected.

In the RBP (*Reservation along the Backward Path*) 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 burst transfer are released as the burst 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 reservation 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 reservation fails due to lack of available wavelengths. This process is repeated until the wavelength reservation 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 burst or reserved by some node pair, $m_w^{(j)} = 0$, otherwise $m_w^{(j)} = 1$.

(5) The arrivals of burst 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 burst 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 a 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 burst 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 burst 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 burst transmission time follows the exponential distribution, it does not directly mean that the service time is given by the burst 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 burst 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 burst 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 node j as the queueing system where the jobs (burst transfer requests) arrive with the general service time with mean $1/T^{(j)}$. Its derivation will be described in the next subsection.

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

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

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 burst 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 $L_a = 0$, $q^{(j)}(1) = 1$ 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 and RBPD protocols. The case of the RFP protocol is 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/RBPD protocols.

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,

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

Due to space limitation, we only present the results (see [5]). The arrival rates of the sum of Classes 1 and 2 are first determined as follows.

$$\gamma^{(a_{h_a})} = e'_a \left[1 - \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^W\right] \times \left[\sum_{k=0}^{W-1} (k+1) \cdot \binom{W-1}{k} \left(\prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^{(k)} \times \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^{(W-k-1)}\right]^{-1}, \quad (2)$$

where

$$e'_a = e_a \times \frac{1}{1 - L_a},$$

which takes account of the retransmissions of bursts. And, we have at link a_i $(1 \le i \le h_a - 1)$,

$$\gamma^{(a_i)} = \gamma^{(a_{i+1})}\phi^{(a_{i+1})}$$

where

$$\phi^{(a_k)} = e^{-\Lambda^{(a_k)}(h_a - k + \frac{1}{2})\cdot D} + \sum_{p=1}^{\infty} \Big[\big(1 - e^{-\Lambda^{(a_k)}(h_a - k + \frac{1}{2})\cdot D}\big)^p \times \big(1 - e^{-T^{(a_k)}(h_a - k + \frac{1}{2})\cdot D}\big)^p\Big]. \quad (3)$$

The first term of Eq. 3 accounts for the event that the other reservation requests are not arrived at the system. The second term of Eq. 3 accounts for the event that the other messages are arrived at the system, however the service time is not beyond the time of $h_a - k + \frac{1}{2}$, and consequently the request on which is focused is accepted. The number of messages is denoted by p. We assume that the burst transfer requests arrive with the general service time, however, for simplicity, we also assume that the service time is obtained by applying the exponential service–time distribution with mean T_j. For arrival rates of Class 1 and Class 2 traffic are then obtained as

$$\alpha^{(a_i)} = \gamma^{(a_i)} \prod_{k=1}^{i-1} \phi^{(a_i)} \quad (4)$$

$$\beta^{(a_i)} = \gamma^{(a_i)} - \alpha^{(a_i)}, \quad 1 \le i \le h_a. \quad (5)$$

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. (4). 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 burst 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 burst 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

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

On the other hand, in the case of the RBPD protocol, we need to consider the case where the NACK signal is forwarded from the intermediate node in the upstream. It is a different point from the RBP protocol, in which the NACK signal is always passed from the source node when the source node finds that no wavelength is available.

In the RBPD protocol, let N_{a_i} be the expected number of links that the RES signal passes by until no available wavelength is found at some intermediate node. While we do not present derivation due to space limitation, it is given by

$$N_{a_i} = \sum_{n=1}^{i-1} n \frac{\prod_{k=1}^{n-1} \chi_{a_{i-k}}(1) \cdot \chi_{a_{i-n}}(0)}{\sum_{m=1}^{i-1} \prod_{k=1}^{m-1} \chi_{a_{i-k}}(1) \cdot \chi_{a_{i-m}}(0)},$$

where

$$\chi_{a_j}(1) = \phi^{(a_j)}; \quad \chi_{a_j}(0) = 1 - \chi_{a_j}(1).$$

Mean wavelength occupation times of the RBPD protocol are then given by

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

The mean wavelength occupation time, $T^{(j)}$, 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

As shown in the previous subsection, the only difference between RBP and RBPD protocols is the wavelength occupation time. Henceforth, the derivation of the blocking probability of the burst transfer requests can be derived in the unified way as follows.

The blocking probability L_a is derived as ([5])

$$L_a = 1 - \left[1 - \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^W\right] \times \prod_{k=1}^{h_a} \phi^{(a_k)} \quad (6)$$

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

$$(1 - L_a)e_a. \quad (7)$$

3.5 Derivation of burst transfer delay

Finally, we consider the burst transfer delay. When the burst transfer request is blocked, the source node retries its request after the backoff time. We assume the exponential backoff time with mean $\theta^{(a)}_{backoff}$.

In what follows, we only show the result for the RBP protocol. In the RBP protocol, the PROBE signal is returned to the source node directly by the intermediate, when the intermediate node finds no available wavelength in the list on the forward path. Such a probability is given by

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

Further, the average number of hops that the PROBE signal is passed is denoted by $\bar{N}$, and is expressed as

$$\bar{N} = \sum_{i=1}^{h_a - 1} i \prod_{l=1}^{i} q_{a_l}(1) q_{a_l}(0).$$

Otherwise, the signal is returned from the destination node, but the wavelength may be used by another burst transfer. By taking these possibilities, the delay until the source node knows that the request eventually fails becomes

$$\begin{aligned}\delta_a = & \left(1 - \prod_{i=1}^{h_a} q^{(a_i)}(1)\right)^W \cdot \bar{N} \cdot D \\ & + \left(1 - (1 - \prod_{i=1}^{h_a} q^{(a_i)}(1))^W\right) \\ & \times \left(1 - \prod_{k=1}^{h_a} \phi^{(a_k)}\right) \cdot h_a \cdot D.\end{aligned}$$

By using the blocking probability derived in the previous subsection, the average number of requests (including a final successful request) for each burst transfer is given by $1/(1 - L_a)$. Then, we have the mean burst delay π_a for node- pair a as

$$\pi_a = h_a D + \left(\frac{1}{1 - L_a^1} - 1\right) \times \left(\theta^{(a)}_{backoff} + \delta_a\right)$$

By unconditioning on a, we finally have the overall mean burst delay as

$$\bar{\pi} = \sum_a e_a \pi_a \,/\, \sum_a e_a \quad (8)$$

4 Performance Results and Discussions

In this section, we evaluate and compare three protocols 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. The mean back off period for node pair a is assumed to be

$$2 \times h_a \times D + 1/\mu_a$$

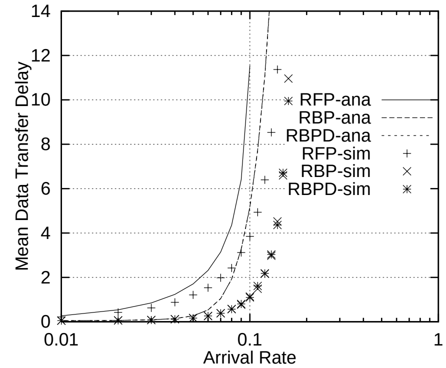
which is large enough compared with the burst transmission time.

Results are shown in Fig. 2 where the average burst transfer delays 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(b), two cases of propagation delays D normalized by the mean burst transmission time are shown; i.e., $D = 0.02$ and $D = 0.2$, respectively. In the figures, the computer simulation results are also shown. As shown in the figures, the RBP protocol outperforms the RFP protocols as expected. It is because the RFP protocol reserves a certain wavelength along the forward path which leads to a larger wavelength occupation time (consisting of wavelength reservation time and wavelength usage time). However, the effect of introducing the backward notification of the NACK signal in the RBPD protocol is very limited. In Fig.2(a), we cannot observe the difference between RBP and RBPD protocols since the smaller propagation delay makes the occupation of the wavelength limited. Thus, as shown in Fig. 2(b), as the propagation delay becomes large, its effect can be observable.

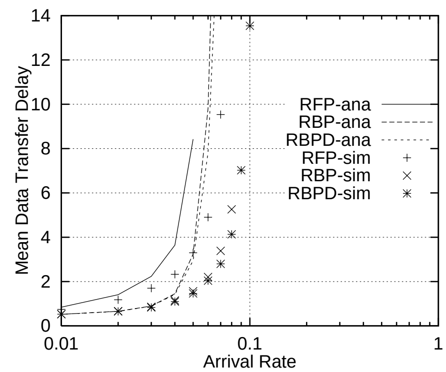
In the above figures, the overall average burst transfer delay are shown. It is easily imagined that the performance of our protocols is dependent the number of hops (i.e, the number of links that the burst experiences). To see this effect, we show the mean burst delays by the hop–count (1 through 4) in Fig. 3. As can be observed in the figure, the delays are increased as the number of hops gets large. The delays in the RBPD protocol are smaller than those in the RBP protocol, but it is limited. It is an inherent drawback in our protocols, but it must be resolved by limiting the number of hops. Fortunately, the photonic network has a capability the pre–determined lightpath is equipped between some photonic cross–connect nodes. In our case, the lightpaths are prepared for long–hop paths, by which the actual number of hop counts can be decreased. Of course, the flexibility of on–demand wavelength reservation are lost in such an approach, and therefore, we need to quantitatively evaluate the effect, which is our important future research topic.

5 Concluding Remarks

In this paper, we have extended our previous approximate method in order to incorporate retrial requests for fast burst transmission protocols. Our results have shown that the RBP/RBPD protocols can improve the performance significantly when compared with the RFP protocol. However, the performance is much dependent on the number of hops, and it should be resolved from a viewpoint of a fairness among connections, which is our future research topic.



(a) Propagation delay $D = 0.02$, the # of wavelength $W = 5$



(b) Propagation delay $D = 0.2$, the # of wavelength $W = 5$

Figure 2: Delay comparisons of three protocols

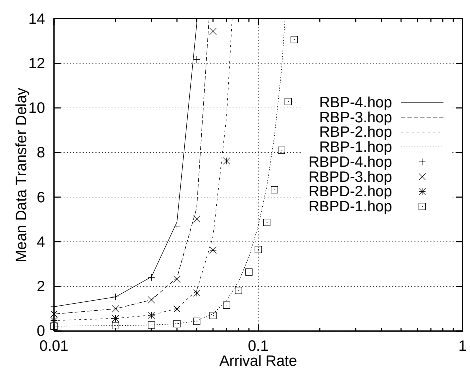


Figure 3: Delays dependent on the number of hops

References

[1] I. Chlamtac *et al.*, "Lightpath communications: An approach to high bandwidth optical WAN's," *IEEE Transactions on Commun.*, vol. 40, pp. 1171–1182, July 1992.

[2] M. Kovačević *et al.*, "Benefits of wavelength tramslation in all-optical clear-channel networks," *IEEE J. Select. Areas in Commun.*, vol. 14, pp. 868–880, June 1996.

[3] X. Yuan, R. Gupta, and R. Melhem, "Distributed control in optical WDM networks," *available at* http://www.cse.buffalo.edu/˜qiao/journal.ps.gz.

[4] A. Sengupta *et al.*, "On an adaptive algorithm for routing in all-optical networks," in *SPIE All-Optical Communication Systems*, pp. 288–299, Nov 1997.

[5] S. Arakawa, K. Miyamoto, M. Murata, and H. Miyahara, "Performance analyses of wavelength reservation methods for high–speed data transfer in photonic networks," in to be presented at *ITC-CSCC '99*, July 1999.