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Performance Analysis of Optical Path/Packet Integrated Networks

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Abstract Hybrid optical architectures combining path and packet switching can be good candidates for future optical networks because they exploit the best of both worlds. In this paper, we propose an analytical model to compute the flow transfer times in a hybrid path/packet switching optical WDM network. We show that a hybrid network with only a few packet switching wavelengths can minimize the transfer time of TCP flows.

Key words Blocking probability, wavelength-division multiplexing, analytical model, hybrid switching

1. Introduction

WDM can use 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 are 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 because a connection may or may not use all the capacity in the dedicated channel. Moreover, path switching needs prior reservation of channels, which adds an additional delay to flow completion time.

A hybrid architecture combining path and packet switching is a possible solution to these problems by exploiting the best of both worlds [1, 2]. There are two main approaches in the literature for realizing a hybrid architecture. One of them is carrying both packet and path traffic on the same wavelength [3, 4]. All wavelengths are principally used by paths. The packet traffic is inserted into idle periods left from the path traffic on the same wavelength. Another method is to use separate wavelengths for path and packet switching and distribute the traffic between them. For example, the network can carry short flows over packet switching wavelengths while carrying the large flows on path switching wavelengths [5]. Both methods need optimization of some parameters of the hybrid switch in order to minimize the flow completion time while keeping the hardware cost low. For example, the switching capacity of packet switching fabric in both methods and the optimum ratio of path and packet-switching wavelengths in the second method should be optimized. Optimization of these parameters requires fast and easy calculation of some performance metrics for path and packet-switched networks.

Several analytical models for calculating the forward and backward blocking rate in path switching have been proposed in the literature [6–13]. Most of them are based on Reduced Load Approximation (RLA) method, which calculates the blocking rates in an iterative manner [14]. In [15], we proposed a novel analytical method, which improves the backward blocking analysis in [6] for more precise results and adapts it for use with Birman's forward blocking analysis for an iterative calculation. We introduced estimation of the state-dependent arrival rate of RESV packets for backward reservation, instead of using an average value like in [6].

In this paper, we propose an analytical model to compute the flow transfer times in a hybrid path/packet switching optical WDM network. Our model can be used for fast and easy calculation of hybrid switching parameters like the optimum ratio of path and packet wavelengths, and the number of path reservation retrials.

The paper is organized as follows. In Section 2., we present a model of the path/packet integrated network. In Section 3., we propose an analytical model for calculating the flow transmission time in a hybrid architecture. Numerical results are presented in Section 4. Section 5. concludes the paper.

2. A model of Path/Packet Integrated Network

Each node in path/packet integrated network consists of IP router and OXC connected by optical fibers.

The path/packet integrated network provides a packet switched network and a circuit switched network by allocating wavelengths for each network. For the packet switched network, the virtual network topology is constructed by configuring a set of lightpaths based on a long-term measurement of traffic volume. When a packet

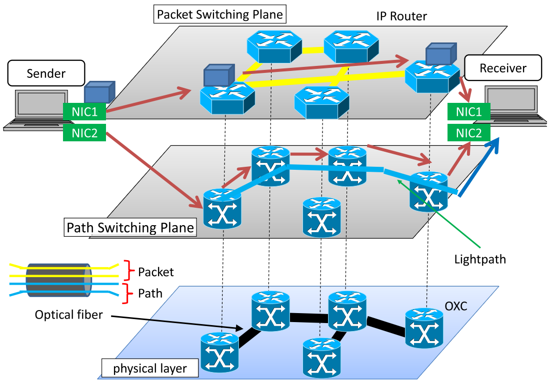

Fig. 1 A network architecture

arrives at a node, the packet is forwarded to the next node in the VNT. In the circuit switched network, when a data transfer request arises, lightpaths are established between source and destination nodes on-demand basis (Figure 1). RSVP-based wavelength reservation protocol is used for lightpath establishments.

Each end-host connecting with the node has two network interfaces; one for inject IP packets into the packet switched network and one for establish a lightpath between two end-hosts. When the data transfer request arises, the end-host selects the packet switched network or the circuit switched network to transfer the data. Various strategies to select the network can be considered. We believe that the optimal strategy highly depends on the traffic characteristics, so the highly sophisticated strategy may be necessary. Instead of chasing the sophisticated strategy, we take a simple strategy to select the network because our primary concern of the current paper is to develop an adaptive wavelength allocation method for optical path/packet integrated networks.

Our simple strategy to select the network is as follows. The sender host first tries to transfer the data in circuit switched network. When the lightpath establishment succeeds, the sender host transfers the data with the transmission capacity of wavelengths. When the lightpath establishment fails, the sender host gives up transferring the data via circuit switched network and transfers the data via the packet switched network. In this case, the sender host uses TCP protocols during the data transfer.

3. Analytical Model

3.1 Path Switching Analysis

We use destination-initiated reservation (DIR) [16] for path reservation. The analytical model is as follows. 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 the Erlang loss model). We assume Poisson flow arrival, which is shown to hold on real core networks where a large number of flows are multiplexed [17]. The 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

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

, where

$$p^n_{m,0} = \frac{1}{1+\sum_{k=1}^{W}\frac{1}{k!}\prod_{j=0}^{k-1}\frac{\alpha^n_{m,j}}{\mu^n_m}}. \tag{2}$$

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 the mutual independence of wavelength distribution between adjacent links, on the second hop of a path, we can write

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

, where

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

if $max(0,i+j-W) \leq k \leq min(i,j)$ and is equal to 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

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

Let e_m be the call setup rate (departure rate of probe packets) and $\lambda^n_{m,k}$ be the arrival rate of probe packets from a node pair m to a 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 $\lambda^1_{m,k} = e_m$. 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, the call setup rate for a 2-hop path, when there are exactly k busy wavelengths on the second link, can be calculated by

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

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

$$\lambda_{m,k}^{n} = e_m(1 - \sum_{i=0}^{W} R(0|W-i, W-k) q_{m,i}^{n-1}). \tag{7}$$

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

$$\gamma_m^d = e_m(1 - q_{m,W}^d) \tag{8}$$

, where $q_{m,W}^d$ is the forward blocking rate of the node pair. These successful call setup requests select an idle wavelength randomly and try to reserve the same wavelength number along the path from destination to source node. The reader is referred to [8] for more detail on forward blocking calculations in Eq. (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_m^n 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 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 interferes 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 $\gamma_{m,k}^n$ be the rate of call setup requests from a node pair m, which reserves 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 $\Lambda_{m,k}^n$ be the total arrival rate of the reservation requests of node pairs interfering with requests from node pair m when there are k busy wavelengths on link n. As a result, $\Lambda_{m,k}^n$ can be calculated by

$$\Lambda_{m,k}^{n} = \sum_{\substack{m' \in M, \\ m'_{n'} = m_n, \\ n' = d(m')}} \lambda_{m',k}^{n'} + \sum_{\substack{m' \in M, \\ m' \neq m, \\ m'_{n'} = m_n, \\ m'_{n'+c'} \neq m_{n+c}, \\ n' \neq d(m')}} \gamma_{m',k}^{n'} \tag{9}$$

for the first $d - 1$ links of node pair m, where the value of λ and γ variables comes from the previous iteration of the algorithm. This interfering traffic causes backward blocking, which decreases the arrival rate of the 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 the interfering traffic arrival is Poisson, we can estimate the arrival rate of reservation requests from node pair m that succeeds in reservation on link $n - 1$ when there are k busy wavelengths on the link $n - 1$ by

$$\gamma_{m,k}^{n-1} = \gamma_m^n e^{-\Lambda_{m,k}^{n-1}(d-n+1)D/(W-k)}. \tag{10}$$

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

$$\gamma_m^{n-1} = \gamma_m^n \sum_{j=0}^{W-1} p_{m,j}^{n-1} e^{-\Lambda_{m,j}^{n-1}(d-n+1)D/(W-j)}. \tag{11}$$

Ref. [6] uses an expected wavelength occupancy ratio for calculating the reservation arrival rates. However, our model improves the calculation of backward blocking by estimating a specific reservation arrival rate for all possible wavelength occupancy ratios by using Eq. (9–11).

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

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

The 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

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

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 Eq. (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, L_m, the blocking probability of a node pair m with hop count d is

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

We used the following algorithm to use these equations to calculate blocking probability by using the 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 values of L_m for each node pair is less than a small constant (we used 10^{-7} in this paper), then finish the iteration. Otherwise, return to step 2 and begin the next iteration.

3.2 Path Retrial

Assume that an incoming call setup request attempts to reserve a connection up to l times until reservation succeeds. The requests that are blocked l times are dropped. For the sake of simplicity, we assume that network conditions at reservation attempts are uncorrelated. Therefore, each attempt has the same blocking probability. The rate of retrials is superimposed on the call setup rate. Let e_m^l be the total call setup rate of a node pair m with a limit of l attempts. e_m^l can be estimated by

$$e_m^l = e_m \sum_{x=0}^{l-1} (L_m)^x. \tag{19}$$

e_m is replaced with e_m^l in Eq. (6–8) to take the extra traffic due to retrials into account. In the RLA method, L_m is first initialized to zero for all the node pairs, so e_m^l equals e_m. e_m^l is calculated by using Eq. (19) and the L_m value from the fourth step of the RLA algorithm and used in the next iteration. The algorithm continues until L_m converges. Finally, we calculate the overall blocking rate L_m^l after l failed reservation attempts by

$$L_m^l = (L_m)^l. \tag{20}$$

3.3 Packet Switching Analysis

We used the TCP performance model from [18] to calculate the transfer time of TCP flows. This model calculates

- P_h: SYN+ACK initial handshake time.
- P_s: The time in slow start.
- P_l: The time for recovering the lost packet at the end of slow start.
- P_c: The time to send the remainder by congestion avoidance.

The TCP transfer time P_m of a flow on a node pair m over the packet network is the sum of P_h, P_s, P_l and P_c. The reader is referred to [18] for their equations. The model requires packet drop rate along the path. When there is optical RAM buffering with wavelength conversion in the packet network, the packet drop rate on each link is calculated by solving the $M/M/c/K$ queuing model where c is the number of packet wavelengths and K is sum of buffer size and number of packet wavelengths. When there is no buffering, the packet drop rate is calculated by $M/M/c/c$ when there is wavelength conversion and by $M/M/1/1$ when there is no wavelength conversion. The TCP throughput and packet drop rates in the network are estimated by using the RLA method iteratively.

3.4 Derivation of Transfer Delays

Let T_m be the average path transfer time of a successfully reserved flow on a node pair m. T_m is the sum of the time spent for successful reservation R_m and the mean occupation time of data transfer φ. In case there is no retrial of failed reservation attempts, R_m equals the round-trip-time of the node pair, so we can say

$$T_m = dD + \varphi. \tag{21}$$

If retrial is allowed, a connection attempt may fail multiple times until it succeeds. Let N_m be the expected number of hops that the reservation packet passes by in case a reservation attempt fails.

$$N_m = \frac{q_{m,W}^{1} + \sum_{n=2}^{d-1} n(q_{m,W}^{n} - q_{m,W}^{n-1}) + d(L_m - q_{m,W}^{d-1})}{L_m}. \tag{22}$$

The last term in the numerator of Eq. (22) implies that the reservation packet traverses all the links along the path in case a forward blocking occurs in the final hop or a backward blocking occurs. A call setup request attempts to reserve a connection up to l times until reservation succeeds, so R_m is

$$R_m = D \frac{(1 - L_m) \sum_{n=1}^{l} (d + (n-1)N_m)(L_m)^{n-1}}{1 - (L_m)^l}. \tag{23}$$

Let F_m be the time spent for a reservation attempt, which eventually fails after l trials. F_m is

$$F_m = lDN_m \tag{24}$$

Then, we can calculate the average transfer time A_m of a flow between node pair m in the hybrid network by Eq. (25) as

$$A_m = (1 - L_m^l)T_m + L_m^l(F_m + P_m) \tag{25}$$

4. Numerical Results

We evaluated the performance of the analytical method on the European Optical Network (EON) topology with the 19 nodes and 39 bidirectional links. Each link carried 16 wavelengths in both directions. The hop delay depends on the propagation delay due to link distance and processing delays influenced by the switching technology used and hardware speed [19]. We used a 10 ms hop delay, which seemed an appropriate value. For the sake of simplicity,

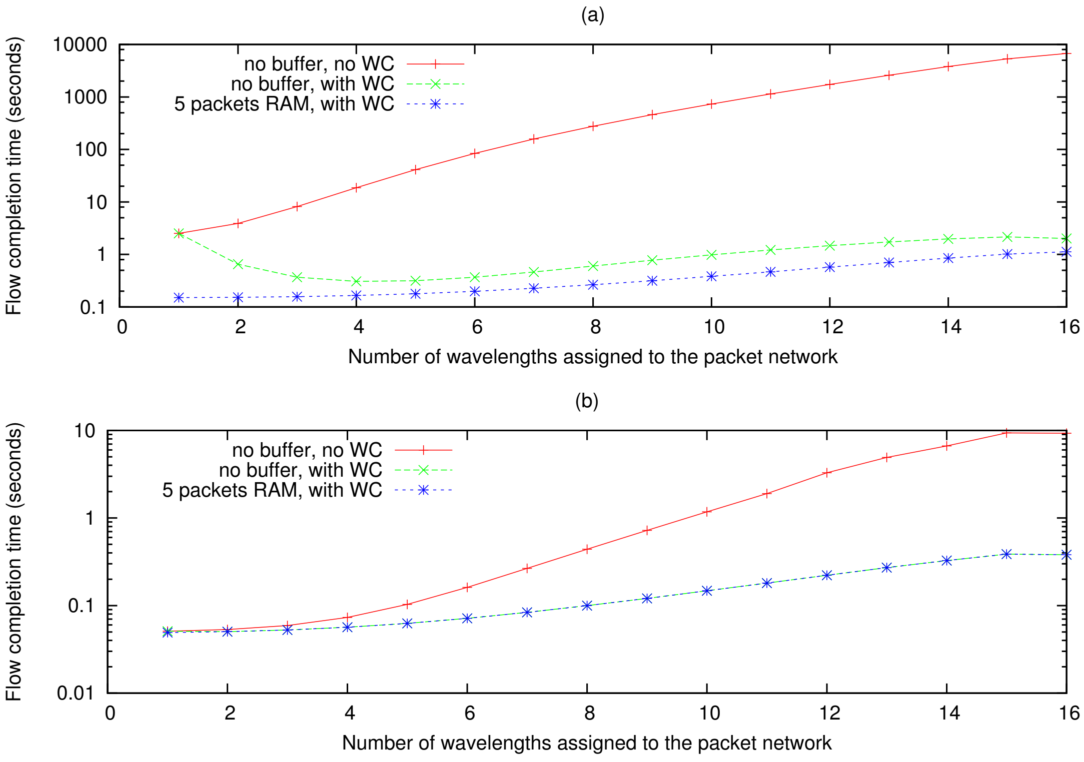

Fig. 2 The average flow transfer times for a flow with size (a) 10^9 Bits and (b) 10^6 Bits.

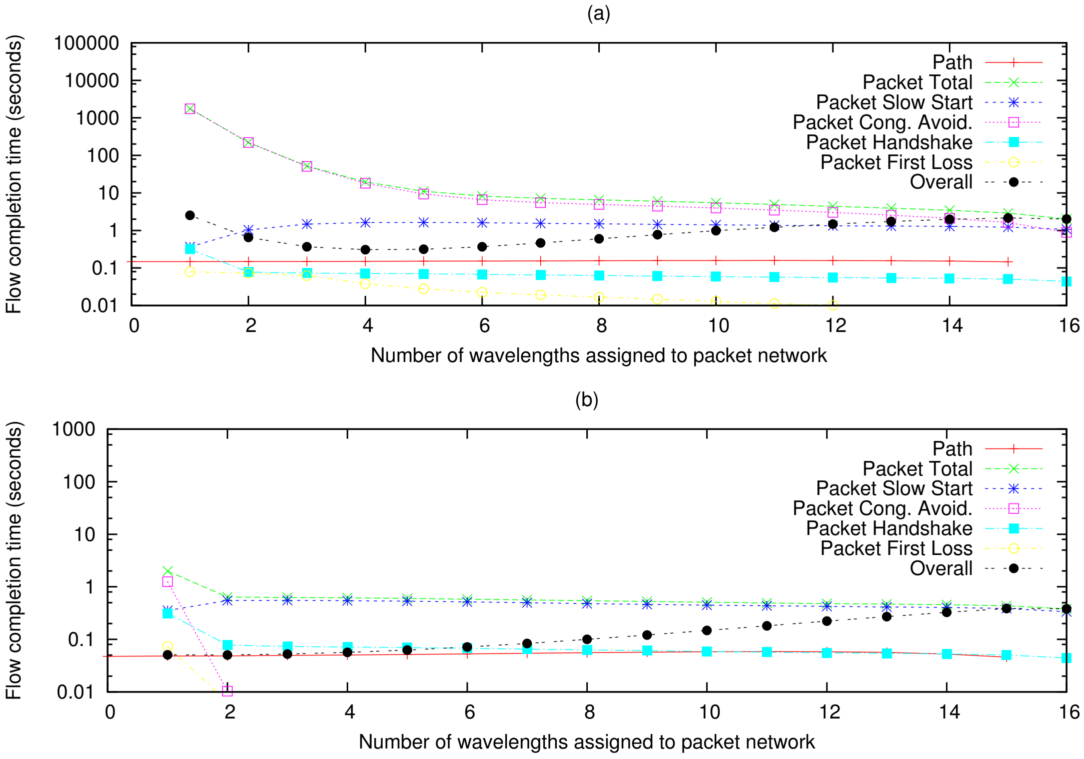

Fig. 3 The comparison of the latencies of TCP states in the packet network and the transfer time of the data flow in the path network for a flow with size (a) 10^9 Bits and (b) 10^6 Bits, when there is wavelength conversion in the packet network without buffering.

we used the same hop delay for reservation packets, data flow on path network and data packets on the packet network on each hop in this paper, but they can be assigned to different values if necessary. The flow holding time had a mean value of 0.1 s. The Erlang loss model is insensitive to connection holding time distribution, but we applied an exponential holding time distribution. We applied a uniform traffic matrix. Flows between each node pair arrived according to a Poisson process. The total reservation request arrival rate in the network was 600 flows/s. Path network allowed two times retrial of failed reservation attempts, which means that the reservation algorithm attempted to do a reservation a maximum of three times.

In a hybrid network architecture, one of the aims is to minimize the overall flow completion time, so the reservation delay is an important metric for a path switching layer. Fig. 2 plots the average flow transfer times for a flow sized (a) 10^9 Bits and (b) 10^6 Bits. The x-axis shows the number of wavelengths assigned to the packet network. Red line shows the case when there is no buffering and WC (wavelength conversion) in the packet network. Green line shows the case when there is WC, but there is no buffering. Blue line shows the case when each link has a buffer sized 5 packets and WC. When the flow size was 10^9 Bits, the flow transfer time was minimized with 5 packet wavelengths when there was WC, but there was no buffering. On the other hand, the flow transfer time was minimized with a single packet wavelength in the rest of analytical results for both flow sizes. When there was a single packet wavelength and no buffering, the drop rate was the same for the case with and without WC, as expected. We can see that the wavelength conversion ability greatly decreased the packet drop rates as we increased the number of packet wavelengths.

Fig. 3 shows the comparison of the latencies of TCP states in the packet network and the transfer time of the data flow in the path network for a flow with size (a) 10^9 Bits and (b) 10^6 Bits, when there is wavelength conversion in the packet network without buffering. When there was WC, using a five packets buffer decreased the flow transfer time for a flow sized 10^9 Bits compared to no buffering in Fig. 2(a), but there was no visible change for a flow sized 10^6 Bits in Fig. 2(b). The reason is that because the 10^6 Bits flow generally completed in the slow start state of TCP before experiencing a packet drop, while the 10^9 Bit flow spent most of its time in the congestion avoidance state as shown in Fig. 3.

5. Conclusions

In this paper, we proposed an analytical method based on reduced load approximation for calculating the flow completion time in hybrid path/packet switching optical WDM networks with destination-initiated reservation with retrial. Such an analytical method can be very useful in the fast calculation and optimization of the traffic splitting parameters for hybrid optical architectures. We presented some the analytical on a mesh EON network and showed that using only a few packet wavelengths can minimize the flow transfer time.

As a future work, we will extend our analytical model with fiber delay line (FDL) based buffering, and we will compare the analytical results with simulation results. Then we will work on an architecture that can adaptively change the ratio of path and packet wavelengths in the network depending on the traffic.

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