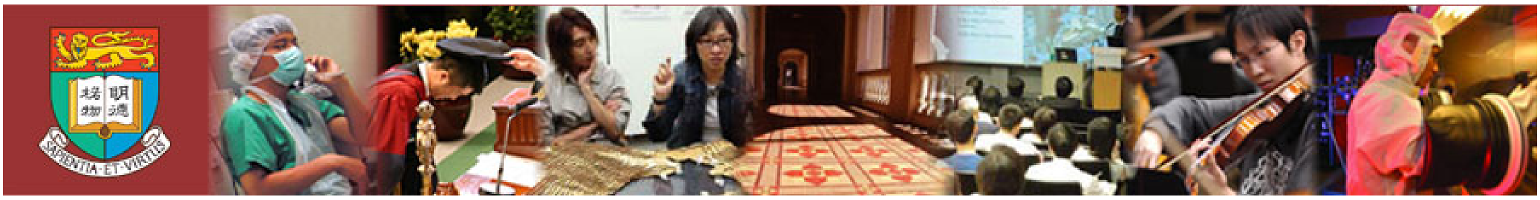

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Performance model of deflection-routed multi-slot batch-transfer networks

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***Abstract*—With the recently proposed multi-slot batch-transfer (MSBT) architecture, we can build optical packet switches using slow switching fabrics with reconfiguration time larger than the guard time between packets. Since MSBT switches can provide multichannel capability with no additional hardware, we propose to combine the multichannel and deflection routing approaches for packet contention resolution in MSBT networks. As there is no analytical performance model available, we derive the required model in this paper. Simulations show that the model is very accurate.**

***Index Terms*—deflection routing, multi-wavelength, multi-slot batch-transfer, optical packet-switched networks**

I. INTRODUCTION

Although terabits per second point-to-point transmission has been realized with optical fiber technology [1], the implementation of a practical optical packet-switched network is still difficult. One problem is the difficulty of guaranteeing high bandwidth utilization, i.e., high packet exchange rate and link utilizations when the fiber transmission rate is high. This is because fast optical switches with reconfiguration time T_{sw} in nanosecond or picosecond range are only available in small sizes such as 2×2 [2]. Large optical switches with up to a thousand ports have been demonstrated using the micro-electro-mechanical systems (MEMS) technology but the required T_{sw} is in milliseconds [3]. Normally, the guard time between packets T_g should be larger than T_{sw}. The system throughput will therefore decrease rapidly with the increase of fiber transmission rate because the packet transmission time T_d will also be shortened accordingly.

Recently, we have proposed a multi-slot batch-transfer (MSBT) switch architecture to solve this problem. With the MSBT architecture, one can use slow switching fabrics with reconfiguration time T_{sw} larger than the packet guard time T_g to build the required optical packet switches [4]. The value of T_{sw} will no longer be important for the system throughput. Consequently, the packet contention problem becomes the main limiting factor for the system throughput. Owing to the lack of effective means to buffer light [5], we propose to combine both multichannel and deflection routing approaches for packet contention resolution in MSBT networks [6], [7]. As there is no analytical performance model available for the deflection-routed MSBT networks, we derive the required model in this paper. One advantage of MSBT networks is that the MSBT switches can provide the required multichannel capability without extra hardware.

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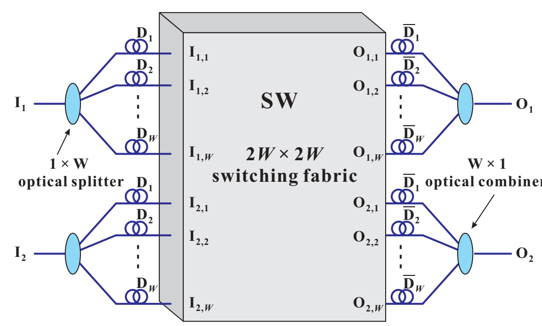

Fig. 1 The multi-slot batch-transfer (MSBT) switch architecture of a 2×2 optical switch [4].

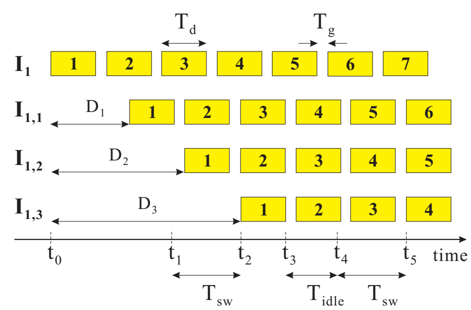

Fig. 2 The timing diagram for the packets at input link I_1 of the proposed optical switch with $W = 3$, where T_d is a packet transmission time, T_g is the required guard time for preventing crosstalk between packets, and T_{sw} is the required reconfiguration time for switch SW.

II. THE MULTI-SLOT BATCH-TRANSFER MULTICHANNEL NETWORKS

Figure 1 shows the multi-slot batch-transfer (MSBT) switch architecture of a 2×2 optical switch where I_1, I_2 and O_1, O_2 are the input and output links, respectively [4]. At each input link, the $1 \times W$ optical splitter and its W fiber delay lines (FDLs) form an optical packet serial-to-parallel (S-P) transmission converter. A packet from an input link I_i is duplicated into W copies with the $1 \times W$ optical splitter and each of the copies is

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delayed by D_i, $i = 1, \ldots, W$ with the FDLs. With the appropriate D_i values, packets from the input link I_i will appear sequentially on the inputs $I_{i,1}$ to $I_{i,W}$ of the switching fabric SW. Figure 2 shows the timing diagram for the packet transfer at the input link I_1 of the MSBT switch with $W = 3$. The incoming packets are delayed by D_1, D_2 and D_3 before they are sent to the inputs $I_{1,1}$, $I_{1,2}$ and $I_{1,3}$ of SW, respectively. At time $t_1 = t_0 + D_3 - T_{sw}$, SW starts to reconfigure itself to prepare for packet transfer. The packets 1, 2, and 3 are finally transferred to the switch outputs in time duration t_2 to t_3 after the completion of the switch internal path setup. At an output link of SW, a $W \times 1$ optical combiner and its associated W sets of FDLs form an optical packet parallel-to-serial (P-S) transmission converter. Packets on the outputs $O_{i,1}$ to $O_{i,W}$ of SW are individually delayed and sent to the $W \times 1$ optical combiner to combine into the optical signal on output link O_i. The delays of the FDLs on the outputs $O_{i,1}$ to $O_{i,W}$ are the complement of that on $I_{i,1}$ to $I_{i,W}$ such that all packets have the same delay in the MSBT switch. Every W time slots, a new batch of W input packets are presented to SW. SW therefore only needs to reconfigure itself once per W time slots to transfer the $2W$ packets to the output links. Using the MSBT switch architecture, we can build optical packet switches using slow switching fabrics with reconfiguration time T_{sw} of up to $W - 1$ time slots [4].

It has been shown in [4] that we can operate the MSBT switches in a time slot interchanger (TSI) mode to reduce the packet contentions. For constant delay requirement, a packet must be assigned to the particular outputs of SW to keep the order of the packet in the W-packet batch at the output link, e.g., a packet at $I_{1,1}$ of Fig. 1 should only be switched to either $O_{1,1}$ or $O_{2,1}$. If delay variance is not a concern, however, the packet can be assigned to the rest of the $W - 1$ outputs of the desired output link to reduce the packet contentions. This TSI mode is equivalent to adding a TSI to each input link of the switch but no additional hardware is needed. A network becomes an MSBT multichannel network (W logical channels per link) if all MSBT switches are synchronized and operate in TSI mode. As in multi-wavelength optical networks, increasing W of the MSBT networks alone will not resolve packet contention. We also have to keep the system loading small to ensure a low packet loss rate, i.e., underutilizing the network. Due to the lack of practical optical buffers, deflection routing is a viable approach for packet contention resolution [5–7]. Since there is no analytical performance model available for the multichannel deflection-routed networks with arbitrary topology, we derive the required model.

III. Performance of Multichannel Deflection Routing

The performance of deflection-routed MSBT networks can be evaluated by using the performance models of deflection-routed multi-wavelength networks, if one is available, because of the similarity between the two kinds of networks. For convenience of illustration, we use the multi-wavelength network as the network model. The corresponding performance model can be used for the MSBT networks after the serial to-parallel/parallel-to-serial conversion time adjustment to the packet delay.

A. The network model

We assume that the multichannel network has N nodes which are arbitrarily connected with optical fiber links and there are W wavelength channels per link. Since deflection routing is used, the numbers of input and output ports of each node in the network are equal. Different nodes can have different degrees (numbers of input/output ports). The network is time-slotted. Packets are checked time slot by time slot at the input links of a node to determine whether the packets should be received or forwarded to the output ports (for transit packets). A K-degree destination node can receive up to KW packets per time slot. However, there are at most W new packets per time slot arriving at each node regardless of the node degree. The new packets are inserted into a node time slot by time slot through a local fiber link with W wavelength channels. The new packets in different channels or time slots of the local link are independent of each other. A node will insert the new packets into the network only if the number of transit packets from its input ports is smaller than the number of output channels. In this paper, a node processes all new packets in an equitable manner. The new packets that exceed the number of available output channels will be blocked regardless of the packet content.

Each packet contains sufficient information for a node to determine the most suitable output port for the packet. We assume full wavelength conversion at the nodes. If more than one channel is available at the packet's desired output port, a node will assign the packet to one of the channels at random. Similarly, the packet will be randomly assigned to any available output channel if no channel is available at the desired output port. At the beginning of a time slot, a node checks all transit and new packets to determine the appropriate output channel assignment. In this paper, the node first assigns output ports to the transit packets. If x transit packets contend for y ($< x$) channels at the same output port, the output channels are assigned to y of the x packets at random. After the transit packet output contention, if there is a new packet and some output channels are available, the node subsequently assigns the output ports. In this paper, the node treats all packets failing the output contention, no matter new or transit, the same way. All unsuccessful contention packets will be assigned available output channels at random. We assume that fiber delay lines have been added to the input ports to delay the packets such that there is sufficient time for output port assignment decision.

B. The analytical performance model

We use the approach in [7] to analyze the throughput delay performance of the network. The packet transfer probability functions of all pairs of input output ports of every node are first derived. We convert the traffic distribution of a node's input links to the offered loads between input and output ports of the node, and apply the packet transfer probability function to compute the node's output link traffic distribution. After repeating this procedure for all nodes, we can finally solve the steady state traffic distribution on all links and compute the system throughput delay performance accordingly [7]. This approach is excellent for modeling networks with arbitrary topology and non-uniform traffic distribution. Furthermore, the computational complexity of this approach will grow linearly with the number of nodes. This is important for modeling the performance of large networks.

We define channel loading ρ_i of an input link i of a K-degree node z as the average time slot utilization of a channel of link i after destination packet filtering. Owing to the channel assignment procedure, $\rho_i = (p_i - d_i)/W$ if there are on average p_i packets per time slot at the input link i and d_i of them are packets with destination z, i.e., non-transit packets. We also define $r_{i,k}$ as the ratio of the transit packets with desired output port k. Let $\mathbf{C}_z(k)$ be the set of destinations of packets that request output port k at node z. Hence, $r_{i,k} = \rho_i^{-1}\sum_{v\in C_z(k)} \ell_{z,i}(v)$, where $\ell_{z,i}(v)$ is the probability of finding a packet destined for node v at a channel of the i-th input of node z. Similarly, we define ρ_0 and $r_{0,k}$ for the new packets arriving at node z. We further assume that the transit traffics in different time slots and different wavelength channels of any input link are also independent of each other. Hence, the numbers of transit and new packets of a node in a slot time become binomial random variables of mean $W\rho_i$, where $i = 0, \ldots, K$. We define $m_{i,k}$ as the number of packets at an input port i with desired output port k. To simplify the notation in the equations, we further define $\mathbf{m_i} = (m_{i,1}, m_{i,2}, \ldots, m_{i,K})$. Let $|\mathbf{m_i}|$ be the sum of all $m_{i,j}$ of input port i, i.e., $|\mathbf{m_i}| = \sum_{j=1}^{K} m_{i,j}$. Since $|\mathbf{m_i}|$ is the number of packets arriving at input port i in a time slot, the probability distribution of the value of $|\mathbf{m_i}|$ being equal to k becomes $P_i(k) = \binom{W}{k}(\rho_i)^k(1-\rho_i)^{W-k}$, where $0 \le k \le W$. Then, the probability distribution of $\mathbf{m_i} = (m_{i,1}, m_{i,2}, \ldots, m_{i,K})$ is a multinomial distribution that can be written in the form of $F_i(\mathbf{m_i}) = P_i(|\mathbf{m_i}|)\prod_{j=1}^{K}\binom{N_{i,j}}{m_{i,j}} r_{i,j}^{\ m_{i,j}}$, where $N_{i,j} = \sum_{k=j}^{K} m_{i,k}$, for all $0 \le i \le K$. We define n_k as the number of channels at output port k that have been reserved by some transit packets at the beginning of a time slot. We also define $\mathbf{n} = (n_1, n_2, \ldots, n_K)$ to simplify the notations. Since the transit packets have priority over the new packets to reserve the output channels and the channel assignment is fair, the probability distribution of $\mathbf{n}$ can be easily computed from $F_i(\mathbf{m_i})$ as

$$R(\mathbf{n}, M) = \sum_{(\mathbf{m}_1,\cdots,\mathbf{m_K})\in T(\mathbf{n},M)} \prod_{i=1}^{K} F_i(\mathbf{m_i}), \qquad (1)$$

where $T(\mathbf{n}, M)$ is a set of combinations of $(\mathbf{m_1}, \ldots, \mathbf{m_K})$ such that $|\mathbf{m_1}| + \cdots + |\mathbf{m_K}| = M \ge \sum_{j=1}^{K} n_j$, and for $1 \le j \le K$ we have the relationship between the $m_{i,j}$ as (i) $\sum_{i=1}^{K} m_{i,j} = n_j$ if $0 \le n_j < W$, and (ii) $\sum_{i=1}^{K} m_{i,j} \ge n_j$ if $n_j = W$. $R(\mathbf{n}, M)$ is the joint probability of the events of n_k channels at output port k being reserved by transit packets when the total number of transit packets is M. The number of transit packets can be larger than W as shown in case (ii) of $T(\mathbf{n}, M)$. We define $X_i(k, h)$ as the probability of a packet from input port i with desired output port k and it is finally assigned to output port h. Given Eq. (1), we can derive $X_0(k, h = k)$, the success probability of a new packet successfully getting its desired output port $h = k$ as

$$X_0(k, h=k) = \frac{1}{W\rho_0 r_{0,h}} \sum_{|\mathbf{m_0}|\le W}\left[F_0(\mathbf{m_0})\sum_{M=0}^{KW}\sum_{|\mathbf{n}|=M}\left[R(\mathbf{n},M)\times \sum_{\mathbf{q}\in S(\mathbf{m_0},KW-M)}\left[\min(a_h, W-n_h)Q[\mathbf{q}\mid\mathbf{m_0}]\right]\right]\right]. \qquad (2)$$

$X_0(k, h = k)$ in Eq. (2) is the average total new packet traffic being successfully sent to output port h divided by the corresponding offered loading ($W\rho_0 r_{0,h}$). In Eq. (2), $\mathbf{m_0} = (m_{0,1}, m_{0,2}, \ldots, m_{0,K})$ represents the set of new packets, and $m_{0,k}$ of them have desired output port k, $k = 1, \ldots, K$. Since a node only serves new packets if the transit packets will not occupy all output channels, $\mathbf{q} = (q_1, q_2, \ldots, q_K)$ represents the set of new packets that can enter the network, where $q_k \le m_{0,k}$. Given an arriving new packet set $\mathbf{m_0}$, the probability of having a served new packet set $\mathbf{q}$ can be solved as $Q[\mathbf{q}\mid\mathbf{m_0}] = \prod_{j=1}^{K}\binom{m_{0,j}}{q_j}$ because of the fair new packet admission assumption. In Eq. (2), $S(\mathbf{m_0}, C)$ is the valid set of $\mathbf{q}$ sets for a given $\mathbf{m_0}$ when the number of available output channels is C, i.e., $S(\mathbf{m_0}, C) = \{\mathbf{q} \mid \mathbf{q} \le \mathbf{m_0}, |\mathbf{q}| = \min(|\mathbf{m_0}|, C)\}$ where $|\mathbf{q}| = \sum_{j=1}^{K} q_j$. Since n_h channels of the output port h have already been reserved by transit packets, only $\min(q_h, W - n_h)$ out of the q_h served new packets can be assigned to the output port h. The summation in the second line of Eq. (2) represents the average new packet traffic being successfully sent to output port h on condition of the new and transit packet arrival sets of $\mathbf{m_0}$ and $\mathbf{n}$. We have Eq. (2) after adding up the conditional new packet traffic on all valid $\mathbf{m_0}$ and $\mathbf{n}$.

When the desired output port k of the set of new packets has insufficient number of available channels, some of the new packets will be randomly assigned (deflected) to the channels of output port h. The number of unassigned new packets from output port k is $\max(0, q_k - W + n_k)$. Since random deflection is used, the number of the unassigned packets to be deflected to output port h is proportional to the ratio of the available channels in port h to the total available channels of all output ports. We define such ratio as $u_h = A(h)/\sum_{j=1}^{K} A(j)$, where $A(j) = \max(0, W - q_j - n_j)$ is the number of available channels in output port j. Similar to Eq. (2), we can write the probability of a new packet to be deflected from its desired output port k to a different output port h as

$$X_0(k,h\neq k) = \frac{1}{W\rho_0 r_{0,k}} \sum_{|\mathbf{m_0}|\le W}\left[F_0(\mathbf{m_0})\sum_{M=0}^{KW}\sum_{|\mathbf{n}|=M}\left[R(\mathbf{n},M)\times \sum_{\mathbf{q}\in S(\mathbf{m_0},KW-M)}\left[u_h \max(0,a_k - W + n_k)Q[\mathbf{q}\mid \mathbf{m_0}]\right]\right]\right]. \quad (3)$$

The new packets have no effect on the channel reservation of transit packets. This much simplifies the derivation of the probability of success of a transit packet to reserve its desired output port as

$$X_i(k,h=k) = \frac{1}{W\rho_i r_{i,h}} \sum_{|\mathbf{m_1}|\le W}\cdots\sum_{|\mathbf{m_K}|\le W} J_h m_{i,h}\prod_{j=1}^{K}F_j(\mathbf{m_j}), \quad (4)$$

where, $J_h = (1 - D_h)$ is the probability of a transit packet successfully reserving a channel from the output port h. D_h can be computed as $D_h = \max\left(0, \left(\sum_{j=1}^{K} m_{j,h} - W\right)\left(\sum_{j=1}^{K} m_{j,h}\right)^{-1}\right)$. Eq. (4) represents the average traffic at output port h from input port i divided by the offered loading to output port h from input port i.

The derivation of the probability of a transit packet being deflected from the output port k to the output port h is more complicated. Similar to that of Eq. (3), the probability of a transit packet losing the contention of output port k to be deflected to the output port h is proportional to the ratio of the available channels in the output port h to the total available channels in all output ports. The computation of the available channels, however, has to also consider the reserved channels by new packets in this situation. Let $v_h = H(h) / \sum_{j=1}^{K} H(j)$ be such ratio of the available channels, where $H(j)$ is the number of available channels at the output port j after considering the new and transit packets of the status sets $\mathbf{m_0}$ and $(\mathbf{m_1}, \mathbf{m_2}, \ldots, \mathbf{m_K})$, i.e., $H(j) = \max(0, W - q_j - \sum_{i=1}^{K} m_{i,j})$. Since the new packet arrival is independent of the transit packet status at the input ports, the probability of a transit packet to be deflected to the output port h can be written as

$$U_h = \sum_{|\mathbf{m_0}|\le W}\left[F_0(\mathbf{m_0}) \sum_{\mathbf{q}\in S(\mathbf{m_0},kW-|\mathbf{m_1}|-\cdots-|\mathbf{m_K}|)} v_h Q[\mathbf{q}\mid\mathbf{m_0}]\right] \quad (5)$$

for each transit packet status set $(\mathbf{m_1}, \mathbf{m_2}, \ldots, \mathbf{m_K})$. Hence, the probability of a transit packet from input port i with desired output port k but being deflected to output port h can be written as the equation of

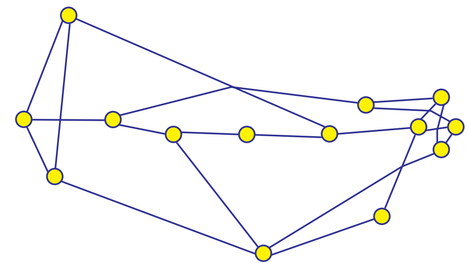

Fig. 3 The NSFNet (1991) network topology. The original map of the network is available from the Internet (ftp://ftp.uu.net/inet/maps/nsfnet/).

$$X_i(k,h\neq k) = \frac{1}{W\rho_i r_{i,k}} \sum_{|\mathbf{m_1}|\le W}\cdots\sum_{|\mathbf{m_K}|\le W} m_{i,k}D_k U_h \prod_{j=1}^{K}F_j(\mathbf{m_j}), \quad (6)$$

where D_k and U_h are defined in Eqs. (4) and (5), respectively.

C. Throughput–delay computation

Given an initial set $\ell_{z,i}(v)$ on all input links, we can use Eqs. (1)–(6) to solve $\eta_{z,i}(v)$ (the probability of finding a packet destined for v at a channel of the i-th output of node z) of all output links. We have $\ell_{y,k}(v) = \eta_{x,h}(v)$ if the h-th output port of node x is connected to the k-th input port of node y. After some iterations, the throughput of a node v (the average number of packets that node v receives in a time slot) can be computed as

$$TH(v) = W \times \sum_{i=1}^{K_v} \ell_{v,i}(v), \quad (7)$$

where K_v is the degree of node v. Using Little's rule [8], we can compute the average packet delay from other nodes to node v as

$$DELAY(v) = TH(v)^{-1} \times W \times \sum_{z=1}^{N}\sum_{i=1}^{K_z} L_z(i)\ell_{z,i}(v), \quad (8)$$

where $L_z(i)$ is the length (in number of time slots) of input link i of node z. Eq. (8) can also compute the average number of hops from all nodes to node v if we set $L_z(i) = 1$ for all i and z.

IV. Model Accuracy

We use simulations on the 8 × 8 Manhattan Street Network (MSN) [9] and NSFNet (Fig. 3) network topologies to demonstrate the accuracy of the model we derived in Section III. In the simulations, we use all assumptions of the network model in Section III-A except that of independent transit traffic. Shortest path routing is used to assign the packet desired output port for each node. The link propagation time is 10 units of the packet transmission time in the 8 × 8 MSN and is proportional to the link length with minimum of 10 units in the NSFNet. We increase the channel loading from 0.01 to 1.0, and record the throughput delay values. Figures 4 and 5 show the analytical

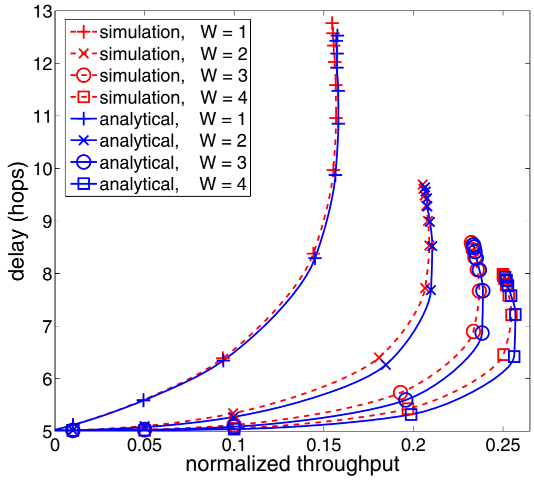

Fig. 4. The analytical and simulation throughput – delay curves of deflection routing on the 8 × 8 Manhattan Street Network [9].

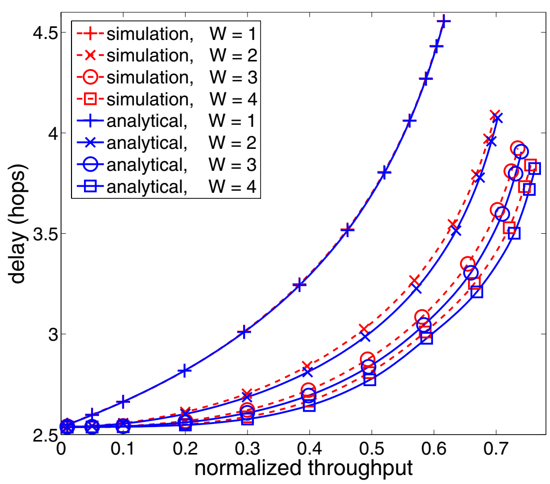

Fig. 5. The analytical and simulation throughput – delay curves of deflection routing on the NSFNet in Fig. 3.

and simulation throughput delay curves of the deflection routing on the 8 × 8 MSN and NSFNet. For the convenience of comparison, the normalized throughput is the number of packets a node received in a unit time divided by W. The delay is in number of hops such that the results can be directly applied to the MSBT networks without the need of S-P/P-S conversion time adjustment. In the figures, the curves with pluses, crosses, circles, and squares are the results from networks with one, two, three, and four channels per link, respectively. We use solid curves for analytical results, and dashed curves for simulations.

From Figs. 4 and 5, the results from the analytical model match those of the simulations very well, especially when each link has only one channel, i.e., $W = 1$. It shows that the traffics in different links are almost independent of each other regardless of the network topology being regular (8 × 8 MSN) or irregular (NSFNet). The analytical model therefore gives very accurate estimation of the system performance when $W = 1$. The traffics in different channels of a link, however, are correlated, though not significantly. Hence, the analytical model also gives results close to those of the simulations when $W > 1$. Nevertheless, both analytical and simulation results confirm the advantage of multichannel networks regardless of the network topology. As shown in Fig. 4, we will have 66% maximum throughput improvement if we send data using 8 × 8 MSN with four 10 Gbps channels per link instead of with a single 40 Gbps channel per link. In multi-wavelength networks, the multichannel capability comes with the hardware cost of transmitters/receivers and wavelength converters. The MSBT networks, however, provide the multichannel capacity with no extra hardware.

V. CONCLUSION

In this paper, we have proposed to combine the multichannel and deflection routing approaches for packet contention resolution in multi-slot batch-transfer (MSBT) networks. Since there is no analytical performance model available for multichannel deflection-routed networks with arbitrary topology, we have derived the required model. Simulation results on 8 × 8 Manhattan Street Network and NSFNet network topologies show that the model is very accurate. We also demonstrate that sending data with low speed multichannel networks may have better throughput–delay performance than with high speed single channel networks. One advantage of the MSBT networks is that the multichannel capability comes with the time slot interchanger (TSI) mode of the MSBT switches. No additional hardware is needed.

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