Analysis of Hot-Potato Optical Networks with Wavelength Conversion

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Abstract— Wavelength conversion has been shown to reduce the probability of blocking in both circuit-switching and packet-switching wavelength routed optical networks (WRONs). The effectiveness of the blocking reduction depends on the topology, and is known to be best for meshed topologies, where the average number of hops per path is large. This paper shows that by exploiting wavelength conversion, routing without buffers, known as *hot-potato*, becomes an interesting option for packet switching WRONs with meshed topologies, such as Manhattan Street (MS) Network and ShuffleNet (SN). The results show that, by using more than 4 wavelengths, a 64 node MS or SN network can work at full load with a hop delay within one hop from its lowest achievable value. We also show that using delay-line routing buffers at the node is a much more effective way of reducing blocking than using wavelength conversion.

I. Introduction

Wavelength conversion has been shown to reduce the probability of blocking in both circuit-switching [1]–[3] and packet switching [4] WRONs. The effectiveness of such reduction critically depends on the topology, and meshed topologies enjoy the largest gain from wavelength conversion [1].

This paper shows that by exploiting wavelength conversion, routing without buffers, known as *hot-potato* [5], becomes an interesting option for packet switching WRONs with meshed topologies, such as Manhattan Street Network and ShuffleNet.

We have already given simulation results of such networks in [6]. In this paper we provide a simple but rigorous teletraffic theoretical analysis. We are able to analytically compare three options for the access scheme at the node. We consider first a costly, centrally managed injection block with tunable transmitters. Next we consider a cheaper scheme in which the transmitters emit on fixed distinct wavelengths and only one packet per wavelength can be injected, but the injection decision is centralized to maximize the number of injections. Finally, we analyze the cheapest scheme in which again the transmitters are fixed, but are independently operated and fed by independent packet streams.

The analysis shows that the cheaper, less "greedy" access schemes give better throughput/delay figures at high loads than the more expensive scheme with tunable transmitters. The results show that slotted hot-potato meshed networks with 64 nodes with more than 4 wavelengths and wavelength conversion can work at full load with a hop delay within one hop from its lowest achievable value (no deflections). The probability of deflection can be made quite low by increasing the number of wavelengths. It is also shown that, for high speed packet switching applications, wavelength conversion in WRONs is a less effective way of reducing blocking than using delay-line routing buffers.

The paper is organized as follows. Section 2 presents the structure of the node, and describes the three access schemes. Section 3 gives the wavelength conversion algorithm used at each node. Sections 4 and 5 present the teletraffic analysis. Results for MS and SN are presented in Section 6, and Section 7 contains the conclusions.

II. Node Structure

The structure of the node in the WRON is shown in Fig. 1a. Two input and output fibers are considered here, although generalizations of the theoretical model are straightforward. The incoming n_w wavelengths from each input fiber are spatially demultiplexed and sent to a stack of n_w submodules, which are centrally controlled and perform the functions of packet add, drop, wavelength conversion, and routing. Packets exiting the submodules are finally remultiplexed onto the output fibers.

The logical structure of the node is shown in Fig. 1b. The node operations are time slotted, and packets (or cells) have a fixed size and are aligned at the node inputs. The node consists of four independently-operated blocks: absorption, injection, conversion and routing. The absorption block removes cells destined to the node. It is assumed that there is one receiver per input wavelength, so that all cells destined to the node can be removed. The injection block decides the transmission of newly generated cells according to its specific access scheme.

We will first assume a *pooled* management of the injection block (PI). We assume the node has n_w *tunable* transmitters. Let $0 \leq G \leq n_w$ be the number of newly generated cells per clock. Let $0 \leq V \leq 2n_w$ be the number of

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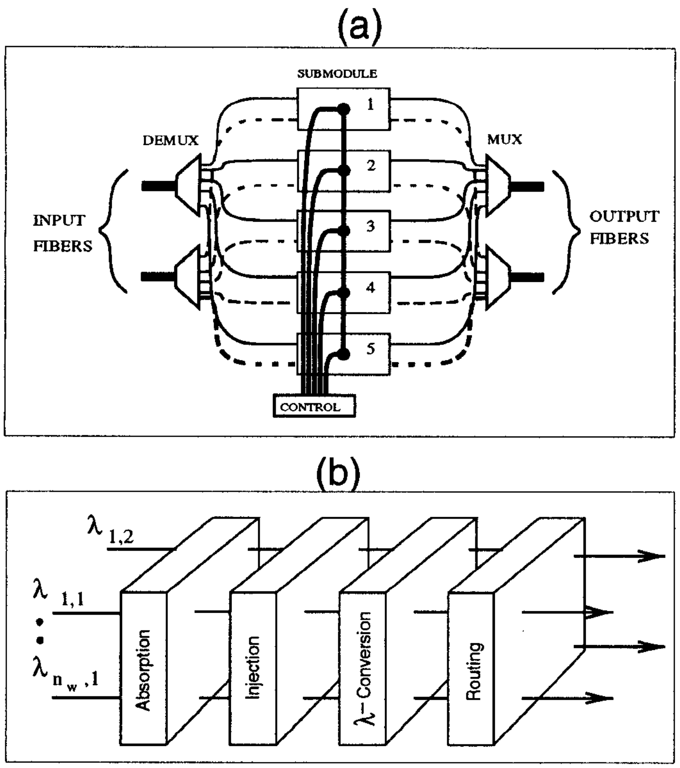

Fig. 1. a) Physical structure of the wavelength conversion node. All the submodules are optically interconnected and there is a central control unit. b) Logical structure of the node.

empty input slots after the absorption block. Then a number $I = min(G, V)$ of new cells are injected at the node, placed at random among the available V empty slots. We assume cells in excess of the available injection slots are discarded. In the PI scheme it may happen that 2 new cells are injected on the same wavelength.

Next we will consider the cheaper case of per-wavelength pooled (PPWI) injections. We assume the node has n_w *fixed* transmitters, one per wavelength. A transmitter can inject a new cell only if there is at least one empty slot at that wavelength after the absorption block. Let $0 \leq W \leq n_w$ be the number of transmitters that can inject a new cell. Then a number $I = min(G, W)$ of new cells are injected at the node, placed at random among the W available wavelengths. Cells in excess of the available injection wavelengths are discarded.

Finally we will consider the simplest case of independent per-wavelength injections (IPWI). We assume the node has n_w *fixed* transmitters. Each transmitter generates a cell independently of the other transmitters at the node. If blocking at that wavelength occurs, the cell is discarded.

The wavelength conversion block has the task of rearranging the cells on the various wavelengths so as to eliminate as many wavelength conflicts as possible.

The injection block has been placed before the conversion block so that conflicts caused by injection of new cells can be solved.

Finally, the routing block is a stack of independent 2x2 switches, one per wavelength, driven by shortest-path algorithm. In case of output conflict at a switch, one of the conflicting cells is selected at random and deflected to the undesired port [5].

III. Wavelength Conversion

At each intermediate node, one or both output fibers may minimize the number of hops a cell has to traverse for reaching its destination. A cell that can take both outputs is called a *don't care cell.* A cell that has only one preferred output is called a *care cell.* Slots on each wavelength at the input fibers can be empty (E), can carry a cell for the node (FN), or a cell that cares to exit on output 1 (C1) or output 2 (C2), or a don't care (DC) cell. A conflict occurs in a submodule when there are two care cells with the same output preference, either (C1,C1) or (C2,C2). To solve the conflicts and avoid deflections at the routing block, we use the following wavelength conversion algorithm:

/* BEGIN */

Step 1.

— **Sort:** conflicting submodules are sorted in (C1,C1) and (C2,C2) sets; Let m= number of (C1,C1) conflicting submodules, and l=number of (C2,C2) conflicting submodules. Assume that $m > l$ (reverse the reasoning otherwise);

— **Swap**: select at random l (C1,C1)-submodules and swap them with the l (C2,C2) submodules, thus eliminating $2l$ conflicts. This eliminates *all* (C2,C2) *minority* conflicts. We are left with only (C1,C1) *majority* conflicts.

Step 2. Solve the remaining majority conflicts (C1 in the example):

Sort: all remaining non-conflict submodules are sorted in two sets: those that do not contain a single C1, and those that do. Consider only those without a C1, and let k be their number. Call this set $\mathcal{R}$. If $k \geq (m-l)$ all conflicts can be solved. Otherwise, select k majority-conflict submodules at random and swap them with the k in the set $\mathcal{R}$. Only $m - l - k$ conflicts are left.

/* END */

IV. Analysis

Define u as the input slot utilization, i.e., the probability that an input slot carries a cell. Define P_{dc} as the probability that an incoming cell is DC. Let r be the probability that an input cell is destined to the node. We make here the usual key assumption that, at every time-slot t, the input slots are independent random variables with the same probability distribution $\mathbf{f_i} = \{Pr[i_j = s], s \in \{E, DC, C2, C1\}\}$, $j = 1, 2, ..., 2n_w$ [8]. From the above definitions, one gets after the absorption block:
$\mathbf{f_i} = \{f_i(E), f_i(DC), f_i(C)\} = \{1 - u(1-r), u\,P_{dc}, u(1 - P_{dc} - r)\}$, and it is assumed that, among care packets, outputs 1 and 2 are equally likely.

We carry on the complete analysis for the case of pooled injections (PI), and in Section V we consider the cheaper PPWI and IPWI options.

We assume the number G of new cell arrivals per node at each clock is a binomial random variable (RV) with trial number n_w and success probability g, which we indicate with $\text{Bin}(n_w, g)$. This corresponds to having n_w independent fluxes of intensity g. We assume the destination of new cells are independent and uniformly distributed over all network nodes excluding the source. Let P_{dc0} be the fraction of DC destinations, i.e., those that can be reached from the source from either output link in the same minimal number of hops. Regularity of the network ensures that half of the remaining care destinations will be for output 1 and half for output 2.

A. *Slot utilization*

At steady state, at each node and clock time, the average number of absorbed cells per wavelength S_{abs} must equal the average number of injected cells S_{inj}, their common value being the throughput per node per wavelength S. Since on average $r\,u$ packets destined to the node reach each wavelength from each input and are all absorbed, we have $S_{abs} = 2\,r\,u$. By Little's law, the throughput per wavelength in two-connected networks is easily shown to be $S = \frac{2\,u}{H}$ [8], where H is the average number of hops, so that one immediately gets: $r = \frac{1}{H}$.

Recalling from Section 2 that $I = min(G, V)$ is the number of injected cells in the PI case, the average number of injections per clock at the node can be expressed as:

$$n_w S_{inj} = E[min(G, V)] \tag{1}$$

where by the independence assumption the RV V is $\text{Bin}(2n_w, f_i(E))$. The expectation in (1) is evaluated by conditioning on G as follows:

$$E[min(G,V)] = \sum_{i=1}^{n_w} P\{G=i\}\times \left(\sum_{j=0}^{i-1} jP\{V=j\} + i(1-\sum_{j=0}^{i-1} P\{V=j\})\right). \tag{2}$$

Solving the equation $S_{abs} = S_{inj}$ gives an implicit expression for u:

$$u = \frac{H\ E[min(G,V)]}{2n_w}. \tag{3}$$

B. *Deflection probability*

Because of the regularity of the considered topologies and the uniform traffic assumption, the global network traffic is a merger of independent, statistically identical traffic streams directed to each destination. Any packet will be a *typical* packet, whose trajectory toward destination can be modeled as a random walk in a homogeneous "gas" of interfering packets [9],[10],[8]. We now evaluate the deflection probability d of a flow-through test cell (TC) entering a care (with respect to its destination) intermediate node, and the deflection probability d_0 of a care TC at its injection node.

Refer again to Fig. 1b. The flow-through care TC is at one of the $2n_w$ inputs and bypasses the absorption and injection blocks, reaching the conversion block.

Since the TC is flowing through, injections can occur only on $2n_w - 1$ slots. Let's fix our attention on an empty slot present at the input of the injection block. We want the probability of the event $\mathcal{U}$={The slot at the output of the injection block is filled with a new cell / it was empty at the input}.

Let $\tilde{V}$ be the number of empty slots besides the one we are considering. Then $\tilde{V}$ has a binomial distribution $\text{Bin}(2n_w - 2, f_i(E))$. Since, given $\tilde{V} = j$ and $G = i$, the probability that our empty slot is filled out of $j+1$ empties is $min[i/(j+1), 1]$, we have

$$P\{\mathcal{U}\} = E\left[min(\frac{G}{\tilde{V}+1}, 1)\right] = \sum_{i=1}^{n_w} P\{G=i\}\times \left(1 - \sum_{j=i}^{2n_w-2} P\{\tilde{V}=j\} + i\sum_{j=i}^{2n_w-2} \frac{P\{\tilde{V}=j\}}{j+1}\right). \tag{4}$$

Therefore, the probability that a slot at the input of the conversion block carries another care packet is

$$f_i'(C) = f_i(C) + f_i(E)P\{\mathcal{U}\}(1 - P_{dc0}), \tag{5}$$

since the slot either already carries a flow-through care, or it is empty and is filled with a new care packet.

Let's now evaluate the deflection probability d. A deflection occurs if the TC enters the conversion block in a submodule with another competing packet, and the contention is not resolved by the conversion block.

Let's consider the configuration of slots at the input of the conversion block. One submodule has, say, a C1 conflict that involves the TC. Also, there are $m-1$ more submodules with a C1 conflict, there are l submodules with a C2 conflict, and there are k submodules without conflict in which a C1 does not appear. The conversion algorithm has thus $l+k$ submodules to swap C1-conflicts with. All C1-conflicts in excess of $l+k$ cannot be solved. Since submodules with a conflict are selected at random for swapping, then given m, l, k (with $m > l+k$) the probability that the TC belongs to a submodule in which a conflict is not solved is $((m-l-k)/m)$.

Hence the probability that a conflict remains in the TC submodule after the conversion block is

$$P(\text{conf}) = \sum_{\mathcal{S}} \frac{m-l-k}{m} P(m,l,k) \tag{6}$$

where $\mathcal{S} = \{(m,l,k) : 1 \le m+l+k \le n_w\, ; m > l+k\}$ is the set of feasible triples where conflicts remain for the TC [1], and where $P(m,l,k)$ is the probability of the triple m, l, k.

[1] For programming purposes it can be found as follows. Fix $1 \le m \le n_w$ (it must be larger than 0 since the TC is among the m majority conflict submodules). Then select the number of minority conflict submodules $0 \le l \le m-1$. However it must be also $m+l \le n_w$. Hence we take $0 \le l \le min(m-1, n_w - m)$. Finally we select the number of non-conflict submodules which can be swapped with majority conflict submodules: $0 \le k \le (m-l)-1$. If k is larger than this, all majority conflicts can be eliminated. Also we must have $m+l+k \le n_w$. Hence the set $\mathcal{S}$ can be expressed as $\mathcal{S} = \{(m,l,k) : 1 \le m \le n_w\, ; 0 \le l \le min(m-1, n_w - m)\, ; 0 \le k \le min(m-l-1, n_w - m - l)\}$.

This can be evaluated as follows. Let $\mathcal{A}$ = {the packet conflicting with TC is C1}. Let $\mathcal{B}$ = {a submodule has a conflict (C1,C1)}. Let $\mathcal{C}$ = {a submodule has a conflict (C2,C2)}. Let $\mathcal{D}$ = {a submodule does not have conflicts nor C1s}. Let $\mathcal{E}$ = {a submodule has only one C1}.

Since injections are operated at random on the available empty slots, the slots at the input of the conversion block remain independent random variables, as they were before injection. Hence we have

$$P(m,l,k) = P\{\mathcal{A}\}\left[\frac{(n_w-1)!P\{\mathcal{B}\}^{m-1}P\{\mathcal{C}\}^{l}P\{\mathcal{D}\}^{k}P\{\mathcal{E}\}^{q}}{(m-1)!l!k!q!}\right] \quad (7)$$

where $q = n_w - m - l - k$, and the term in square brackets is a multinomial probability. It is easily seen that

$$\begin{cases} P\{\mathcal{A}\} &= f_i'(C)/2 \\ P\{\mathcal{B}\} &= P\{\mathcal{C}\} = (f_i'(C)/2)^2 \\ P\{\mathcal{D}\} &= (1-f_i'(C)/2)^2 - (f_i'(C)/2)^2 = (1-f_i'(C)) \\ P\{\mathcal{E}\} &= 2(f_i'(C)/2)(1-f_i'(C)/2) \\ &= 1 - P\{\mathcal{B}\} - P\{\mathcal{C}\} - P\{\mathcal{D}\} \end{cases} \quad (8)$$

The TC is then deflected if it looses the coin toss, i.e. with probability $d = P(\text{conf})/2$.

As for the initial deflection probability of a care TC at its injection step, d_0, this is obtained as in (5)–(8), the only difference being in equation (4), where now G, the number of newly generated packets excluding the TC, cannot be more than $n_w - 1$, i.e. is distributed as $\text{Bin}(n_w - 1, g)$.

C. Throughput and Delay evaluation

The previous results can be put together to get the desired expressions of the throughput $T(g)$ and the hop delay $D(g)$ as functions of the parameter g, the generation probability. The procedure involves the solution of a 2x2 system of nonlinear equations. We start with an initial guess of the quantities $[d, d_0]$. Then, following the method in [8], the average number of hops H and the probability of don't care P_{dc} can be easily obtained as functions of $[d, d_0]$ only [8]. Then $r = 1/H$ is obtained. Next $u = u(g, r)$ is evaluated as outlined in section IV-A. Finally, new values for $[d, d_0]$ are obtained as in section IV-B. The process is repeated up to convergence of $[d, d_0]$.

V. Simpler Access Schemes

The next two subsections extend the analysis to the simpler access options PPWI and IPWI described in Section 2.

A. Pooled Per-Wavelength Injections

Let's consider the case of pooled per-wavelength injections (PPWI). The number W of wavelengths at which at least one empty slot is at the input of the injection block has a binomial distribution $Bin(n_w, 1-(1-f_i(E))^2)$. The average number of packets injected per node is, as in (1):

$$n_w S_{inj} = E[min(G, W)]. \quad (9)$$

Now let's consider the deflection probability of a flow-through care test cell. Equations (6) and (7) still hold in this case, but the probabilities of events $\mathcal{A}$ through $\mathcal{E}$ are different.

Consider event $\mathcal{A}$ first. As in (8) we have

$$P\{\mathcal{A}\} = (f_i(C) + f_i(E)P\{\mathcal{U}\}(1-P_{dc0}))/2. \quad (10)$$

The probability $P\{\mathcal{U}\}$ that a slot after the injection block is filled with a cell is found as in eq. (4), where $\tilde{V}$ is now replaced by the number $\tilde{W}$ of wavelengths, excluded the TC wavelength, on which an injection is possible. This RV has a binomial distribution $Bin(n_w - 1, 1-(1-f_i(E))^2)$.

Now consider event $\mathcal{B}$. A (C1,C1) after injection is possible only if it was already present at the input, or if there was an (E,C1) or (C1,E), and the E was filled with a C1:

$$P\{\mathcal{B}\} = \left(\frac{f_i(C)}{2}\right)^2 + 2\frac{f_i(C)}{2}f_i(E)\frac{P\{\mathcal{U}\}(1-P_{dc0})}{2}. \quad (11)$$

By symmetry, $P\{\mathcal{C}\} = P\{\mathcal{B}\}$. Now, the probability that the E is filled, $P\{\mathcal{U}\}$, is slightly different from case $\mathcal{A}$, since now the number $\tilde{W}$ of available wavelengths for injection (excluding the one under consideration for event $\mathcal{B}$) is $\tilde{W} = X + Y$, where RV X is distributed as $Bin(n_w - 2, 1-(1-f_i(E))^2)$ and accounts for the available wavelengths except the TC wavelength; and where the RV Y is $Bin(1, f_i(E))$ and accounts for the TC wavelength.

We use again eq. (4), where $\tilde{V}$ is replaced by $\tilde{W}$:

$$P\{\mathcal{U}\} = E\left[min(\frac{G}{\tilde{W}+1}, 1)\right] = P\{Y=0\}\times E\left[min(\frac{G}{X+1}, 1)\right] + P\{Y=1\}E\left[min(\frac{G}{X+2}, 1)\right]. \quad (12)$$

Now consider event $\mathcal{D}$. We have

$$P\{\mathcal{D}\} = \left[\left(1 - f_i(E) - \frac{f_i(C)}{2}\right)^2 - \left(\frac{f_i(C)}{2}\right)^2\right] + \left\{2\left(1-\frac{f_i(C)}{2}\right)f_i(E) - f_i(E)^2\right\}\left(1 - \frac{P\{\mathcal{U}\}(1-P_{dc0})}{2}\right) \quad (13)$$

because a wavelength after the injection block has no conflicts nor C1s if this is true when injections cannot take place (expression in square brackets, similar to that in (8)), or when they can (expression in curly brackets), and a C1 packet is not injected (last expression in brackets). $P\{\mathcal{U}\}$ is as in case $\mathcal{B}$.

Finally, to evaluate the initial deflection probability d_0, we use again expressions (6), (8), where the probabilities of events $\mathcal{A}$ through $\mathcal{E}$ must be recomputed as follows. Since the TC is generated and injected, then on its wavelength no other injection is possible and thus $P\{\mathcal{A}\} = f_i(C)/2$.

In the evaluation of $P\{\mathcal{B}\}$ and $P\{\mathcal{D}\}$, we note that G in (4) is now distributed as $Bin(n_w - 1, g)$, and $\tilde{W}$ is distributed as $Bin(n_w - 2, 1-(1-f_i(E))^2)$.

B. Independent Per-Wavelength Injections

Let's consider the cheapest option of non-coordinated per-wavelength injections (IPWI).

Here the average number of packets injected per wavelength simply is

$$S_{inj} = g(1 - (1 - f_i(E))^2) \quad (14)$$

which is the equivalent of (1). For this case there is a closed expression for u [8]:

$$u = \frac{\sqrt{r^2 + g^2(1-r)^2} - r}{g(1-r)^2}. \quad (15)$$

In the evaluation of the deflection probability d of a flow-through care test cell, equations (6) and (7) still hold, and the probabilities of events $\mathcal{A}$ through $\mathcal{E}$ are the same as in the PPWI case, eqs. (10), (11), (13), by simply changing $P\{\mathcal{U}\}$ in g. The evaluation of the initial deflection probability d_0 is identical to that of d, the only difference being in the expression $P\{\mathcal{A}\} = f_i(C)/2$ as in the PPWI case.

VI. Results

In this section we will give teletraffic performance curves for a 64-node ShuffleNet (SN64) and a 64-node Manhattan Street network (MS64), which are known to have very similar topological properties, and hence similar performance [11].

Fig. 2 shows hop-delay H versus throughput per wavelength S obtained by the analytical model, for a number of wavelengths n_w increasing from 1 to 15, for the three access schemes considered. In the figure, solid lines indicate the costly pooled injection (PI) access scheme, which performs worse than the cheaper PPWI and IPWI schemes (dotted and dashed lines respectively, overlapped in the figure).

As n_w increases, the delay decreases and the throughput increases. The first substantial improvement occurs when increasing from 1 to 2 wavelengths, and then gradually, the improvement becomes more and more marginal for larger values of n_w. This is similar to the improvement obtained in single-wavelength deflection routing networks when adding routing buffers at the node [11], since wavelength conversion avoids blocking and thus deflections, as buffers do.

Note that using more than 4 wavelengths brings the hop count H within one hop from its lowest (zero deflection) value.

Fig. 3 shows deflection probability against link load u. We note that at light loads the PI scheme gives lower deflection probability, but as the load increases the less greedy schemes PPWI and IPWI give lower deflection probability, although the difference is small. This is due to the fact that less injections allow the conversion block to work more efficiently, thus reducing deflections. This means that a less "greedy" access strategy does improve the throughput/delay performance at high load. A similar result was obtained in [8] when comparing different access schemes in single-wavelength hot-potato networks. In any case, PPWI and IPWI behave almost identically. Thus the cheaper IPWI scheme should be preferred.

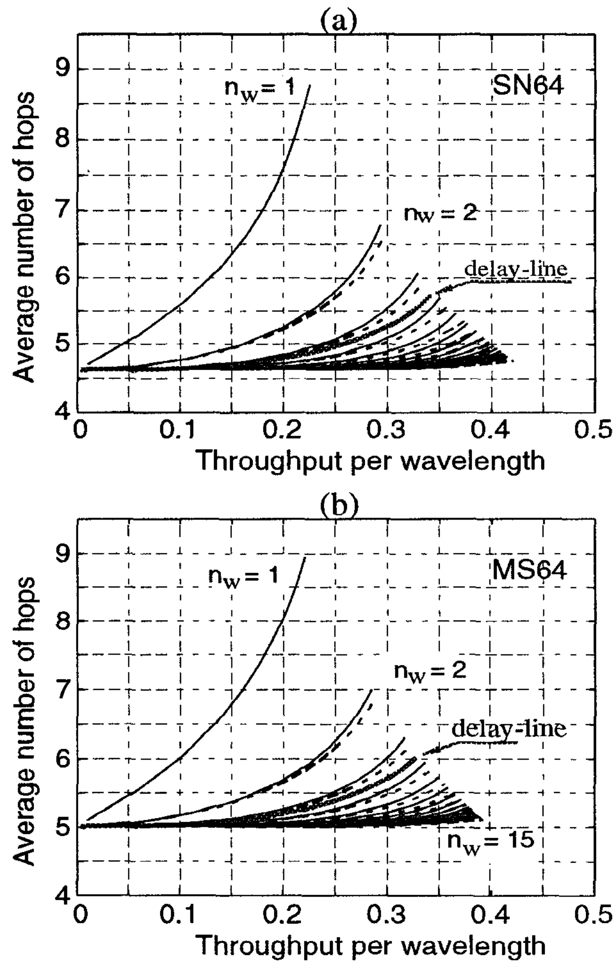

Fig. 2. Average number of Hops H vs Throughput per wavelength S [cells/slot] in 64-node ShuffleNet (a) and Manhattan Street (b). Number of wavelength as a parameter: $n_w = 1, 2, .., 15$. Solid lines: pooled injections (PI); Dotted lines: pooled per wavelength injections (PPWI); Dashed lines: independent per-wavelength injections (IPWI). Delay-line: indicates a single wavelength network with 1 optical buffer at the node [11].

As in Fig. 2, we note that the effect of increasing the wavelengths is similar to that of increasing buffers in single-wavelength networks. We note for example that we can keep the deflection probability below 10^{-9} with $n_w = 15$ wavelengths only at loads below $u = 0.2$ in SN and 0.22 in MS. As the load increases, the possibility of conflict increases and deflections set in, even with a large number of wavelengths.

Returning to Fig. 2, we can compare the effectiveness of wavelength conversion to that of standard delay-line buffering. The bold line curve indicates the delay/throughput performance of a single-wavelength network where a single delay-line optical routing buffer is provided at the nodes [11]. Such buffer and its control has been proven to be optimal [7]. More than 3 wavelengths are needed to match the contention resolution capability of the delay-line. Con-

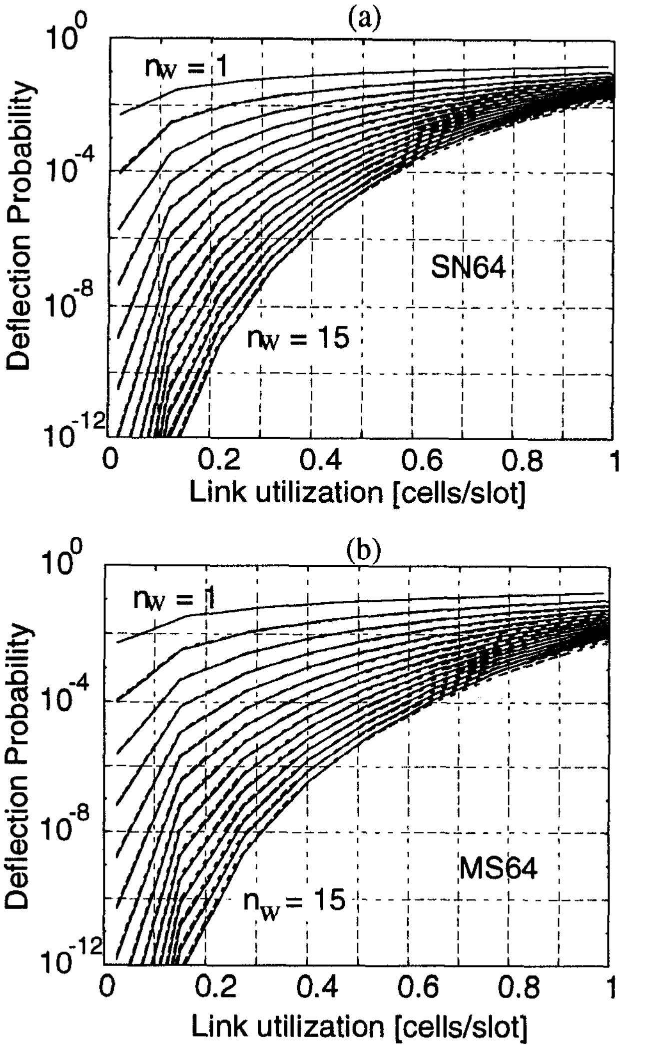

Fig. 3. Deflection probability at care nodes d vs link utilization u [cells/slot] in 64-node ShuffleNet (a) and Manhattan Street (b). Number of wavelengths as a parameter: $n_w = 1, 2, .., 15$. Solid lines: pooled injections (PI); Dotted lines: pooled per wavelength injections (PPWI); Dashed lines: independent per-wavelength injections (IPWI).

tention resolution by delay lines is more effective than wavelength conversion. In fact, with a careful control, the number of care cells stored in the buffer (the ones causing contentions) can be made much smaller than the number of care cells circulating in the network (the ones causing contentions in wavelength conversion).

VII. Conclusions

We have shown that slotted hot-potato meshed networks with 64 nodes with more than 4 wavelengths and wavelength conversion can work at full load with a hop delay within one hop from the zero-load hop delay. The probability of deflection can be made quite low by increasing the number of wavelengths but as the load increases, the number of required wavelengths becomes prohibitively large.

It has been shown here that the simplest non-coordinated per-wavelength access scheme works more efficiently than the other more complex and "greedier" schemes considered, and should therefore be preferred.

An important conclusion of this study is that, for packet switching applications, wavelength conversion in WRONs is a less effective way of reducing blocking than using delay-line based routing buffers. However, the main elements in favor of wavelength conversion are: 1) it can suppress the accumulation of noise such as amplifier spontaneous emission and crosstalk [12] for on/off keying modulation; and 2) it doesn't introduce extra delay, as buffers do, this being a minor plus for high speed packet switching.

Acknowledgments

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