

Optical Wavelength Routing, Translation, and Packet/Cell Switched Networks

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Abstract—We study several models for fixed-size packet/cell switching (e.g., 53 bytes for asynchronous transfer mode) in wavelength routed optical networks with an emphasis on throughput performance analysis. In particular, we examine the associated trade-offs between functionality and hardware complexity. The basic model here is a two-sided “switch” or sorter. Cells generated at user inputs destined for user outputs are allowed to reach their destinations by recirculation or multihop through a fixed wavelength routed optical network a number of times. Using algebraic techniques, we analyze the basic model and its variations that use different types of wavelength translation for their capability to achieve permutations of cells from inputs to outputs. In particular, we showed that when cell-by-cell wavelength translation functionality is allowed, the number of recirculations in the network to achieve all permutations is $3 \log_w N$ where W is the number of wavelengths. The resultant normalized per user throughput of $1/3 \log_w N$ is close to the conjectured optimal of $1/(2 \log_w N - 1)$ under the conditions specified in the model. Finally, using another model we show that it is possible to achieve a normalized per user throughput of 1 and we calculate the amount of extra hardware required for this purpose.

I. INTRODUCTION

WAVELENGTH routed optical networks using wavelength cross-connects [4], [7]–[10], [12], [14] to provide wavelength reuse and wavelength division multiplexing (WDM) have been proposed. Such networks use cross-connects which can be fixed or dynamically reconfigured with the ability to achieve any permutation of input to output ports independently for each of W wavelengths, $\lambda_1, \lambda_2, \dots, \lambda_W$. Access stations transmit optical signals into the network using a single fiber and receive optical signals from the network by using a single fiber. In this work, we consider end users attached to these access stations communicating with other users using fixed packets or cells. The cell size could be 53 bytes, as is the case in the asynchronous transfer mode (ATM). Wavelengths in the network are used to establish optical connections among access stations such that the connections remain in place for long periods of time. Connections are established among access stations by selecting a path between them on a wavelength and setting the cross-connect states for the chosen wavelength in an appropriate manner. Fig. 1 shows wavelength λ_i reused along edge disjoint paths which do not have any links in common. Wavelength routing allows the connections on wavelengths between access stations in

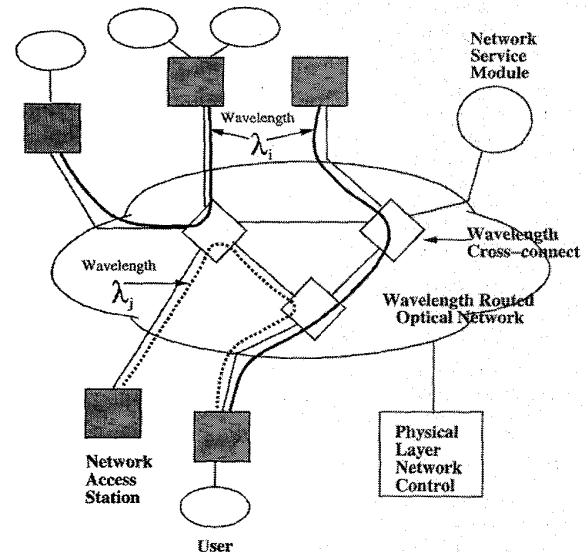


Fig. 1. Wavelength routed optical network.

the network to be reconfigured to support changing internodal traffic and connectivity requirements, or to respond to faults. However, the wavelength routed optical networks considered here are essentially fixed. Although we allow for reconfiguration of the optical network, such changes occur at much longer time scales than individual cell times.

This study is based on a basic two-sided “switch” or sorter model for cell switching over a fixed multiwavelength optical network. By studying the sorting properties of several variations of this basic model, we develop an understanding of the role for wavelength translation in cell switching over wavelength routed networks. In the basic model, users attach to access stations, which are in turn connected directly to a multiwavelength optical network. We consider variations of this basic model that offer different types of wavelength translation capabilities at the access stations. Using algebraic techniques, we analyze each model for its ability to achieve all cell permutations from the input to output.

II. BASIC TWO-SIDED MODEL OF NETWORK

We consider the network to be two-sided with user inputs on one side and user outputs on the other. The inputs and outputs are numbered from 1 to N . The users attach to access stations which are connected to a wavelength routed optical network using a single fiber in each direction for network access. The users insert and remove cells to and from the access stations.

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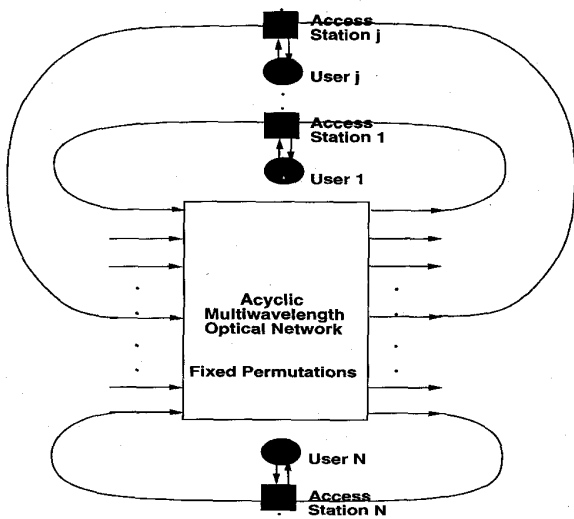


Fig. 2. Basic two-sided model.

In turn, the access stations insert and remove the cells from the optical network. In this model, the network is wrapped around so as to colocate the inputs with the outputs. At this point, we do not assume that the access stations have electronic switches in them. We leave open the possibility that the cell switching in the access stations might be all-optical. Furthermore, since buffering is difficult in all optical implementations, we place a great deal of emphasis on unbuffered solutions.

Based upon earlier work [3] on oscillating optical cycles, we require that the optical network be acyclic, i.e., the optical network has no cycles in it. Also, in these idealized models we assume that the delays incurred by the different cells in traversing the optical network are the same. We examine the conditions under which all $N!$ permutations (one-to-one mappings) of cells from the user inputs to outputs are allowed in the network. Later, we will comment on expanding the model to allow for many-to-one and one-to-many mappings of the cells from inputs to outputs.

Previous work [5] has studied the permutation capabilities of “single-hop” multiwavelength networks. In these single-hop networks, permutations of connections are achieved in one pass through a multiwavelength optical network by changing the state of switches/cross-connects in the optical layer or by tuning optical transmitters and/or receivers at the periphery of the optical network. For single-hop networks, the tradeoffs between using space division switching and wavelength routing were studied.

In this work, we consider cell switching over multiwavelength optical networks. Since the size of each cell is small (53 bytes), it would be unrealistic to require the optical network to change its switching state each time a cell were to be transported to its destination. Also, we wish to avoid placing any tuning requirements on the optical transmitters and/or receivers. In this basic model, the optical network uses a constant number of wavelengths to establish long term (much longer than individual cell times) optical connections among access stations. Hence, the optical layer is fixed, i.e., the set

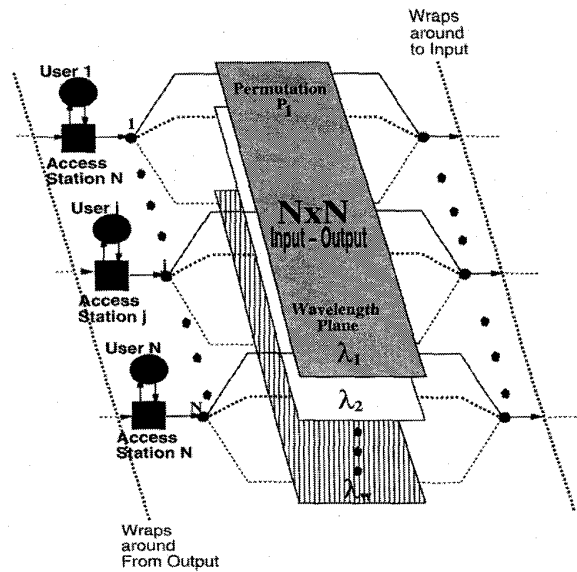


Fig. 3. Model 1: Multiwavelength network, simple wavelength translation, unbuffered access stations.

of permutations allowed through it is a fixed small number. Also, each access station uses an array of fixed (not tunable) and distinct optical transmitters and receivers. Observe that if only one pass through the fixed optical network is allowed, the set of achievable cell permutations is a small number equal to the permutations offered by the multiwavelength optical network (see Fig. 2). Hence, in this model and all its variations, the access stations allow cells to reach their destinations by recirculating (similar to multihop [1] when the access stations perform optoelectronic conversions) back through the optical network multiple times. This is equivalent to taking multiple products of the fixed permutations offered by the optical network. We examine the capability of these networks to achieve all cell permutations. In this work, we analyze variations of this basic model.

A. Model 1: Multiwavelength Network, Simple Wavelength Translation, Unbuffered Access Stations

1) *Features of Model 1:* In this model (see Fig. 3), each access station has an array of W lasers/receivers transmitting/receiving on wavelengths $\lambda_1, \lambda_2, \dots, \lambda_W$ and has only one user connected to it. Furthermore, each access station is unbuffered. Note that the number of ports into the optical network is N . Fig. 3 shows the optical network with W wavelengths that are set up to provide one permutation P_i per (logical or virtual) wavelength layer i . Although the figure shows each wavelength layer separated out in space, the layers are virtual and are controlled independently of each other.

Consider N cells at user inputs that are destined for outputs (one-to-one mappings only). As described below, the access stations offer a simple wavelength translation function. First time around the network, the N cells at the user inputs are required to choose the same wavelength, thereby accessing the same wavelength layer (permutation). A cell chooses

wavelength layer i by selecting the corresponding laser at wavelength λ_j for transmission. Each time the cells recirculate, they are allowed to rechoose the wavelength layer by translating their wavelengths. However, all cells are restricted to choose the same wavelength layer. Hence, the network provides a simple wavelength translation capability.

2) *Analysis of Model 1:* Consider a single permutation P set up in the optical network as described below.

$$P = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 4 & 3 \end{pmatrix}.$$

In one pass through the optical network, a cell at input 1 is routed to output 2, a cell at input 2 is routed to output 1, a cell at input 3 is routed to output 4, and a cell at input 4 is routed to output 3. Thus, in one pass through the network, only permutation P_1 is achievable. Observe that, in multiple passes around the network, products of permutation P_1 are also achievable. Hence, in Model 1, the set of cell permutations from input to output supported by the network $P(N)$ is given as follows:

$$\begin{aligned} P(N) &= \langle P_1, P_2, P_3, \dots, P_i \dots P_W \rangle \\ &= \{ \pi_1 \cdot \pi_2 \cdot \pi_3 \dots \pi_j \dots \pi_t : \\ &\quad \pi_j \in \{ P_1, P_2, \dots, P_i \dots P_W \}; \\ &\quad j = 1, \dots, t \} \end{aligned} \quad (1)$$

where t is the number of times that the cells circulate around the network.

3) *Question A:* Does the set $P(N)$ from (1) include all permutations by choosing appropriate permutations $P_1, P_2, P_3, \dots, P_W$?

4) *Observations:* To answer this question, we analyze the model from a group theoretic perspective [2], [6]. The W permutations can be considered as generators for the group $P(N)$. Each time the cells reenter the optical network layer, they can translate their wavelengths to the same wavelength λ_i . This allows them to choose permutation P_i , which is one of the W permutations (generators). This operation routes the cells to destinations specified by P_i , thereby creating a new ordering (permutation) of the cells. In successive passes through the optical network, the cells are operated on by other permutations P_j until they get to their desired destinations. In the Cayley graph representation of the above, the vertices are the $N!$ permutations of the symmetric group S_N (group of all $N!$ permutations) and a directed edge from node P (or permutation P) to node Q (or permutation Q) represents the action of one of the W generators. One of our concerns is the diameter, or the length of the longest shortest path, of this Cayley graph, given that we use a fixed constant W number of generators. Since each edge of the Cayley graph represents the action of one of the generators, the diameter of the Cayley graph represents the maximum number of recirculations required to reach the desired destination user cell permutation when starting from the identity.

5) *Fact A:* We can choose four permutations (two generators and their inverses) for the group S_N so that the diameter of the corresponding Cayley graph is $O(N \log N)$.

6) *Comment on Fact:* The generators are discussed in [2] along with the proof that they generate the entire symmetric group S_N . For instructional purposes, we consider a different example of two generators: the transposition and the N -cycle. These two generators or permutations can be represented as shown below:

$$\begin{aligned} P_1 &= \begin{pmatrix} 1 & 2 & 3 & 4 & \dots & N \\ 2 & 1 & 3 & 4 & \dots & N \end{pmatrix} \\ P_2 &= \begin{pmatrix} 1 & 2 & 3 & \dots & N-1 & N \\ 2 & 3 & 4 & \dots & N & 1 \end{pmatrix}. \end{aligned}$$

It can be shown that they perform the "bubblesort" operation and, hence, the diameter of the resulting Cayley graph is $O(N^2)$. The theorem shown below follows from these comments.

7) *Theorem 1:* Four wavelengths in the multiwavelength network of Model 1 (simple wavelength translation and unbuffered access stations) can be used to support all permutations of cells from input to output with $O(N \log N)$ recirculations in the network. The corresponding normalized per user throughput of $O(1/N \log N)$ is the best possible under these conditions.

We can set up four permutations (see Fact A) on $W = 4$ wavelengths in the optical network. The resulting normalized per user throughput in this model is $O(1/N \log N)$ which is the best possible under these conditions. This model is important since it shows that it is possible to achieve all permutations of user input cells to outputs using simple unbuffered access stations and a simple wavelength translation capability.

In the next model, we significantly improve the throughput and the hardware port count by using cell-by-cell wavelength translation capabilities at the access stations.

B. Model 2: Multiwavelength Network, Cell-by-Cell Wavelength Translation, Unbuffered Access Stations

1) *Features of Model 2:* Consider the multiwavelength optical network shown in Fig. 4. The figure shows W multiple virtual wavelength layers that are set up to provide one permutation P_i per wavelength layer λ_i . Although the figure shows each wavelength layer separated out in space, the layers are virtual and are controlled independently of each other, in general. As before, each access station is unbuffered and has an array of W lasers/receivers transmitting/receiving on wavelengths $\lambda_1, \lambda_2, \dots, \lambda_W$. However, as shown in Fig. 4, W users are "clustered" together and are attached to one access station. Each access station has one fiber into and out of it. The station multiplexes the W wavelengths onto a single fiber for transmission. Also, W wavelengths coming out of the single fiber from the optical network are demultiplexed at an access station. Hence, there are N/W access stations in the network each with one optical input and output to and from the optical network.

An important difference is that the access stations allow independent cell-by-cell wavelength translation. Each time a cell comes back to recirculate, it can rechoose its wavelength

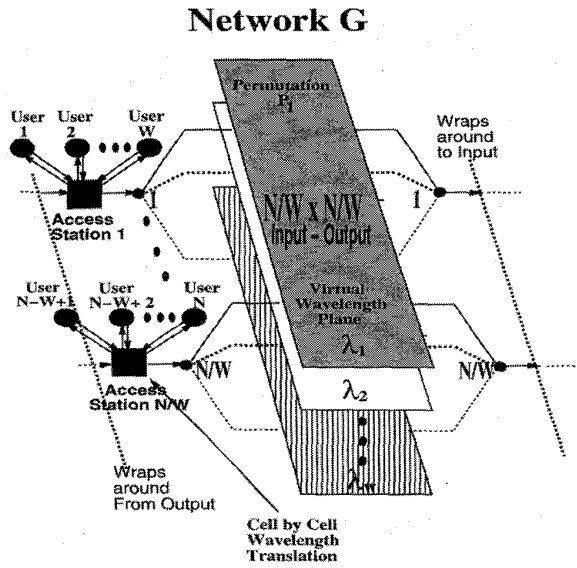


Fig. 4. Model 2: multiwavelength network, cell-by-cell wavelength translation, unbuffered access stations.

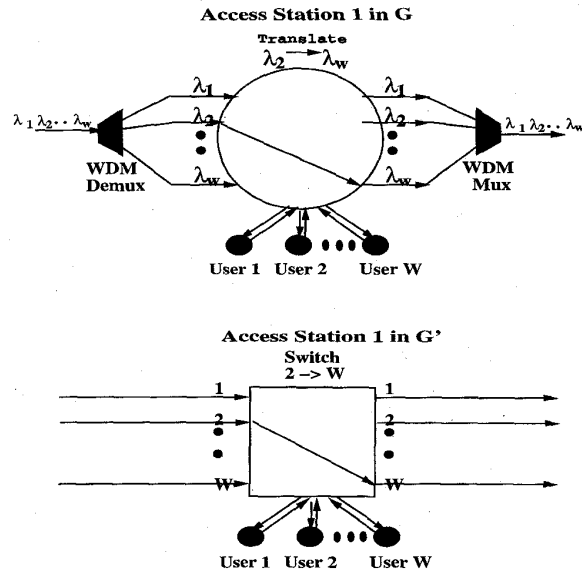


Fig. 5. Access station.

independent of the cells at other access stations. We now list some of the optical constraints on the network.

- A wavelength routed network must not allow any operation that permits two or more signals on the same wavelength to reach the same output in optical network (Color Clash).

- Cells can independently translate their wavelength at an access station, with the constraint that no two of the W cells require to be translated to the same wavelength

2) Analysis of Model 2: Now we turn our attention to the analysis of the allowable cell permutations from the user inputs to outputs. In the following, we create an equivalent setting which makes it easier for analysis.

a) Analysis for equivalent network G' : Consider the N/W inputs and outputs to the optical network G , as shown in Fig. 4. We create an equivalent network G' with N inputs and outputs in which the single input and single output of every access station in G is “expanded” to represent W inputs and outputs (see Figs. 4–6). Wavelength λ_1 on input 1 of G is represented as input 1 of G' , λ_2 on input 1 of G is represented as input 2 of G' , etc. Wavelength λ_1 on input 2 of G is represented as input $W + 1$ of G' , λ_2 on input 2 of G is represented as input $W + 2$ of G' , etc. In general, wavelength λ_i on input k of G is represented as input $(k - 1)W + i$ of G' . The above is also done for the outputs.

For each wavelength λ_i , replace the corresponding virtual wavelength plane representing permutation P_i by an equivalent fixed space division configuration. For example, say input port k is connected by wavelength λ_i to output port j in G . In G' , a fixed space division connection is created from port $(k - 1)W + i$ to $(j - 1)W + i$. Next, replace each cell-by-cell wavelength translating access station in G by a space division switch of size $W \times W$ in G' (see Figs. 5 and 6). Consider access station k in G . The access station k (input k to optical network G and output k from optical network G) translates the wavelengths of the cells that enter

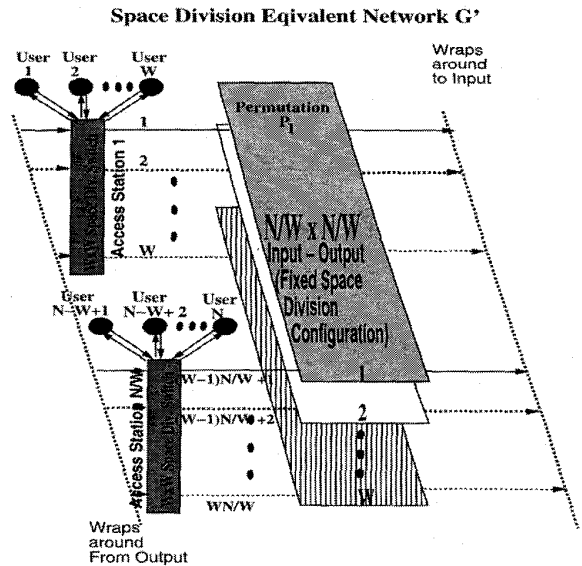


Fig. 6. Space division equivalent network G' .

it from output k of the optical network, subject to constraint 2 (Color Clash) mentioned above. The wavelength translated cells on wavelengths λ_1 to λ_W are then reinserted into the optical network on input k . Say, a cell on wavelength λ_i coming into access station k is to be translated to wavelength λ_j , before reentering the network. The equivalent operation required of the access station k in G' would be to switch the cell from port $(k - 1)W + i$ to port $(k - 1)W + j$ at the access station. Fig. 5 shows an example. At access station 1 in G a cell on wavelength λ_2 is to be translated to λ_W . The equivalent operation at access station 1 in G' is to switch input 2 to output W . Thus, each cell-by-cell wavelength translating access station in G can be replaced by an equivalent $W \times W$ space division switch (cell-by-cell switching times) in G' , with

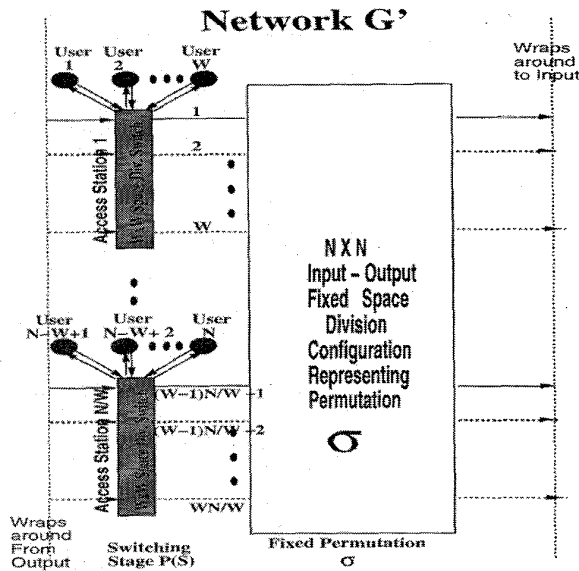


Fig. 7. Another representation of space division equivalent network G' .

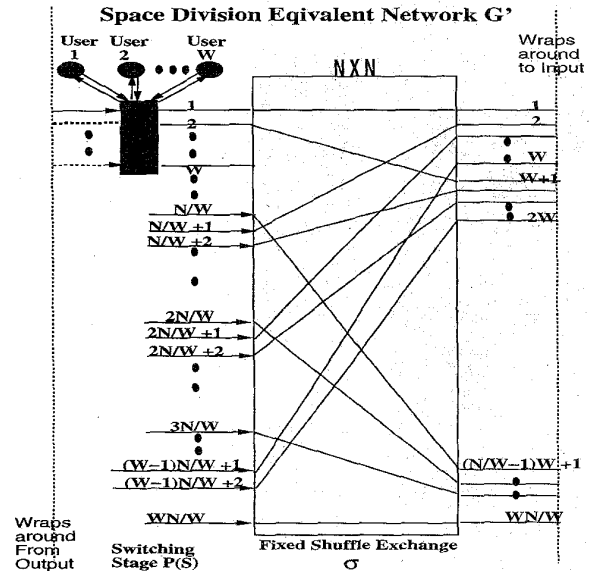


Fig. 8. Equivalent network G' with shuffle-exchange.

W access lines from the users. Note that the access lines from the users simply carry cells in and out of the access stations.

Fig. 6 shows the network G' . It is clear that G' is functionally equivalent to the network of Fig. 4. In fact, it is not difficult to see that G' is basically the **space division** equivalent of the multiwavelength network G . Thus, we can study the properties of the equivalent network G' . G' can also be represented as shown in Fig. 7. Here, the entire middle space division layer of Fig. 6 representing the different wavelength layers in the optical network G is collapsed into one permutation σ between N inputs and outputs in the network G' .

Fig. 7 representing G' is similar to a multistage switching network in which the access stations represent switching stages separated by fixed connection patterns (permutation σ). Hence, the set of cell permutations $P(N)$ allowed by G' is

$$P(N) = \sigma P(S_1) \sigma P(S_2) \sigma \cdots \sigma P(S_t) \quad (2)$$

where t is the number of times that the cells circulate around the network, and $P(S_i)$ is the permutation obtained when the space division switches at the access stations in G' are collectively in switching state S_i . In the original network G , the switching stage permutation $P(S_i)$ represents the equivalent cell-by-cell wavelength translation performed at the access stations.

3) *Question B:* Does the set $P(N)$ from (2) include all permutations? Alternatively, does $P(N)$ realize the symmetric group S_N ?

4) *Observations:* We would like to set up a single permutation σ in G' such that $P(N)$ from (2) realizes all permutations.

5) *Fact B:* The group $P(N)$ shown in (2), representing the recirculating multistage network G' realizes the symmetric group where σ represents the "shuffle-exchange" permutation [18]. The number of recirculations can be shown to be $3 \log_W N$.

6) *Comments on Fact:* It has been shown that shuffle exchange type multistage networks can be used to generate all permutations with $3 \log_W N$ stages. (Actually, the result was improved to show that $3 \log_W N - 4$ stages are sufficient [18], [11], [15], [19]). We can set up permutation σ (Fig. 7), to provide a shuffle exchange permutation in G' such that $P(N)$ includes all permutations. As explained above, the number of recirculations required will be $3 \log_W N$. Fig. 8 shows an example of the shuffle-exchange permutation on G' . Note that $N = W^k$ where k is an integer variable. Now the final step is to find a wavelength allocation scheme that will allow us to achieve the shuffle exchange permutation in the multiwavelength network G such that optical constraints 1 and 2 (basically Color Clash) mentioned above are satisfied.

7) *Wavelength Allocation Scheme:* First, we assign labels $\lambda_1, \lambda_2, \dots, \lambda_W$ to the edges in the shuffle exchange permutation of Fig. 8. The labels are assigned as shown in Fig. 9; so as to satisfy the Color Clash constraint in G . Observe that each successive collection of W outputs in G' is assigned a cyclic shift of labels with respect to the previous W outputs. This is done in order to prevent a Color Clash. Now, we embed the shuffle exchange permutation in network G . Replace the space division switches in G' by cell-by-cell translating access stations shown in Fig. 5. Replace each successive collection of W input and output ports of the optical network in G' by a single port in G . The same wavelengths are assigned between each pair of ports in G , as the wavelength labels that are assigned between the corresponding collection of W ports in G' .

Fig. 10 shows an example of the shuffle exchange on the space division equivalent network G' , with $N = 8$ and 2×2 space division switches at the access stations. Fig. 11 shows the wavelength labeling scheme that avoids the Color Clash condition. Fig. 12 sets up the shuffle exchange on the corresponding multiwavelength network with $W = 2$. Based on the above, Theorem 2 can be stated as follows.

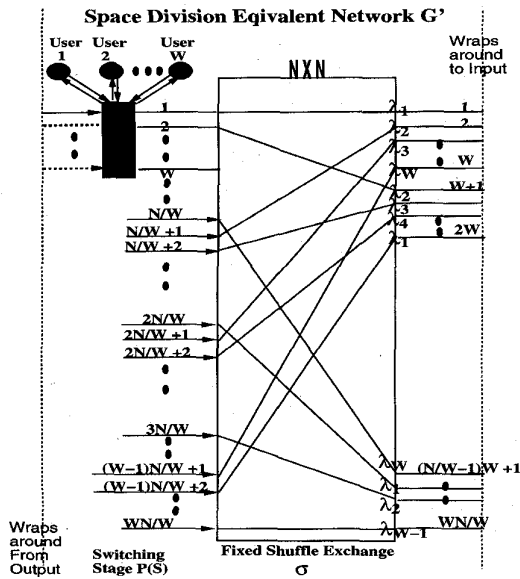


Fig. 9. Wavelength label assignment in equivalent network G' with shuffle-exchange.

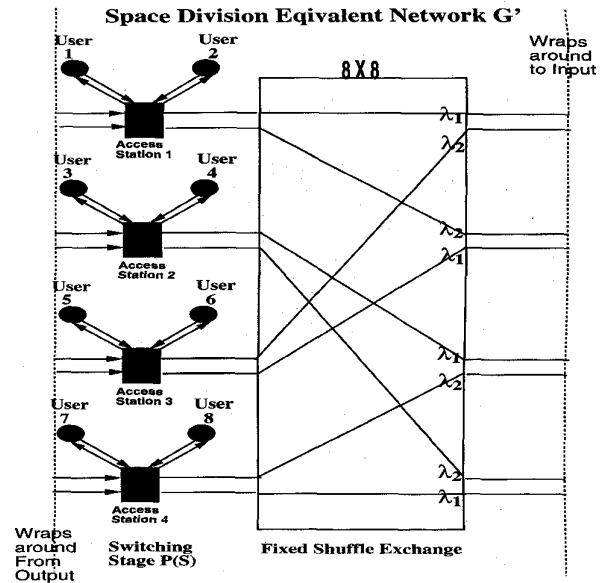


Fig. 11. Wavelength assignment in equivalent network G' with shuffle-exchange using 2 wavelength labels.

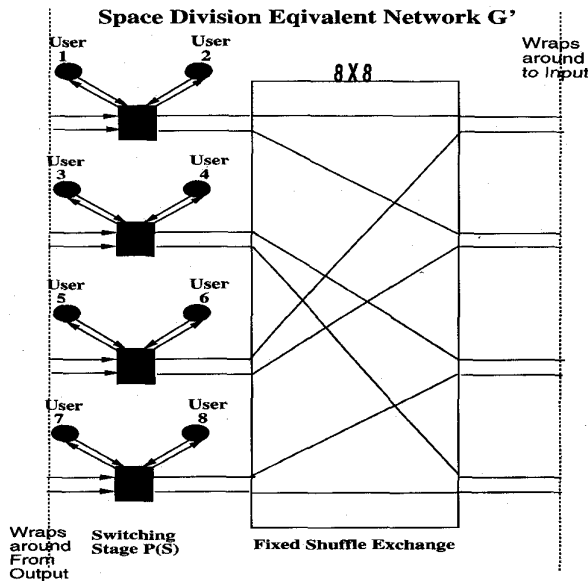


Fig. 10. Equivalent network G' with shuffle-exchange using 2×2 switches at access stations.

8) *Theorem 2:* The multiwavelength network of Model 2, using cell-by-cell wavelength translation and unbuffered access stations, supports all permutations of input cells to output cells with $3 \log_W N$ recirculations and a fixed number of W ($W > 1$) wavelengths. The corresponding normalized per user throughput of $1/3 \log_W N$, is within a constant factor of the optimal under these conditions.

We would like to find a permutation element σ such that the group $P(N)$ (2) representing network G or G' realizes the symmetric group S_N , with at most $2 \log_W N - 1$ (conjectured best [19]) products. In fact, it is conjectured that using the shuffle-exchange $2 \log_W N - 1$ stages (recirculations) are

sufficient [19]. However, this problem is still open in the literature. Alternatively stated, the permutation σ from (2) that permits the network G to allow all permutations with $2 \log_W N - 1$ recirculations is unknown.

In the following Model 3, we show that a normalized throughput per user of unity can be achieved and we calculate the amount of extra hardware required to achieve this result.

C. Model 3: Multiwavelength Network, Cell-by-Cell Wavelength Translation, Unbuffered Access Stations, Normalized Unity Throughput

Consider the network shown in Fig. 12 with $W = 2$. Cells recirculate through the same optical network a number of times, thereby reusing permutation σ a number of times ($3 \log_2 N$) before being sorted to their destinations. During the time that the cells are being sorted to their destinations, more cells from the user stations cannot be allowed into the network. Hence, as explained earlier, the per user normalized throughput is $1/3 \log_2 N$.

However, the network could be built so as to comprise multiple stages (see Fig. 13), with the cells entering at one end and leaving at the other. The optical fabric with permutation σ set up as the shuffle exchange (two wavelengths used to achieve σ in each stage), is spatially repeated $3 \log_2 N$ times separated by "cell switching" stages. Observe that, as compared with Model 4, the same optical fabric with permutation σ is not reused in a "time division" manner. Hence, cells can be inserted continuously by the users at the inputs. This results in a normalized per user throughput of 1.

Note the extra hardware in this model as compared to Model 2. In fact, we could "stack up" the switching stages by folding them over onto the access stations at the inputs in column 1. We could also stack up the $3 \log_2 N$ optical permutation stages σ one on top of each other to create one optical network

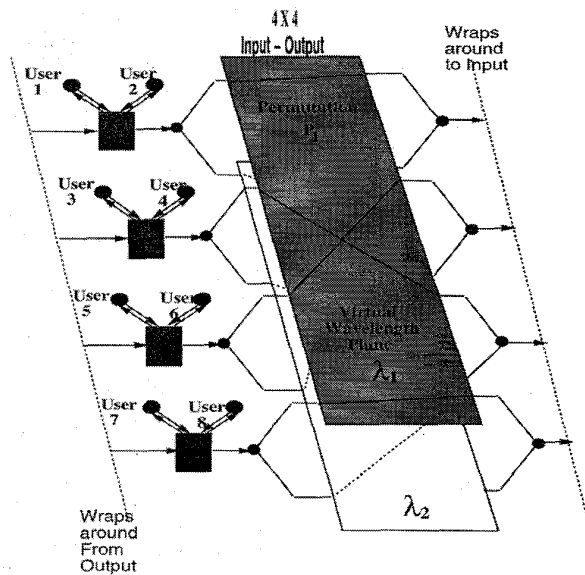


Fig. 12. Wavelength routed network G with shuffle-exchange set up on 2 wavelength planes (virtual).

fabric. We would require $W = 2 \times (3 \log_2 N)$ wavelengths in the optical network by using two wavelengths to set each equivalent stage of σ . The important conclusion from Model 3 is: by adding extra hardware to the network it is possible to achieve a normalized per user throughput of unity.

In the following sections, we comment on other issues that are of importance here, i.e., many-to-one and one-to-many mappings, buffering, and processing. We also state that electronic ATM/packet switches can be used at the access stations to provide the desired cell-by-cell translation functionality.

III. ROLE FOR ELECTRONIC SWITCHES IN PROVIDING WAVELENGTH TRANSLATION FACILITIES

In this section, we argue that the use of electronic ATM/Package switches at the access stations is advantageous. This is because these switches provide the desired cell-by-cell wavelength translation capabilities required in Models 2 and 3, along with the added benefits of buffering and processing (routing). First, let's discuss some of the benefits of processing and buffering.

Consider the case where the access stations are provided with some processing (routing) and buffering capabilities. Some very interesting work regarding routing of permutations with fixed buffer sizes can be found in [13]. This work has some applications here with modifications. In general, adding processing (routing) and buffering capabilities at the access stations can potentially reduce the number of recirculations in the network thereby increasing the throughput. Buffering also allows the network to accommodate the probabilistic behavior of the cell arrivals and the existence of nonuniform propagation delays through the network.

As we had mentioned in the introduction, we will briefly discuss the expansion of the model to include "many-to-one" and "one-to-many" cell patterns. Consider the "many-to-one"

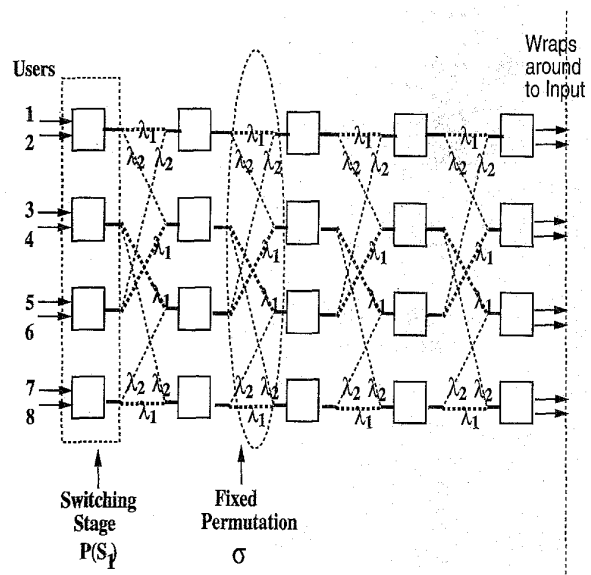


Fig. 13. Multistage wavelength routed network of model 3.

case, where cells from many inputs are intended for the same destination user. In this case, we have no choice but to buffer the cells, so that only one cell is allowed to reach the destination at any given time. However, the case of "one-to-many" multicasting is very interesting. Consider the case where the same cell is intended for multiple destinations. In this instance, it will be interesting to study the effect of providing multicast capability in the optical network [17] and/or in the access stations. This is an open issue which needs to be addressed. In summary, buffering and processing capabilities are important to the building of distributed cell/packet switched networks.

We also know from Section II-B (also Fig. 5), that electronic ATM switches can be used at the access stations to provide the required cell-by-cell wavelength translation. Electronic ATM switches can also provide us with the additional advantages of buffering and processing. Hence, it is advantageous to use electronic ATM or packet switches at the access stations to provide the required cell-by-cell wavelength translation.

IV. CONCLUSION

We studied several models for fixed-size packet or cell switching in wavelength routed optical networks. Using algebraic techniques, we analyzed a basic two-sided switch model and several variations for their capability to achieve permutations of cells from inputs to outputs. Cells were routed to their destinations by recirculating through a fixed multiwavelength optical network a number of times.

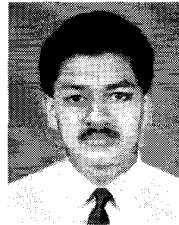
Model 1 considered a multiwavelength optical network with simple wavelength translation facilities at the access stations. Based on group theoretic results, we showed that four wavelengths were sufficient in the modeled unbuffered network to realize all permutations with $O(N \log N)$ recirculations where N is the number of users. This resulted in a normalized per user throughput of $O(1/N \log N)$, which is close to the optimal achievable under these conditions. As

an improvement to Model 1, multiwavelength network Model 2 allowed each cell to independently translate its wavelength each time it recirculated through the network. In this case, it was shown that using W wavelengths ($W > 1$) set up as a shuffle-exchange, it is possible to achieve all permutations in $3 \log_W N$ recirculations in the modeled unbuffered network. Furthermore, it was shown that the number of ports to the optical network can be decreased by a factor of W to N/W . The normalized per user throughput in this case is $1/3 \log_W N$, which is close to the optimal under these conditions. In Model 3, we showed that it is possible to achieve a normalized per user throughput of one, and calculated the required amount of extra hardware. In particular, we showed that $3 \log_2 N$ copies of the multiwavelength optical network separated by cell switching and cell-by-cell wavelength translating stages achieves the desired result.

We argued that using intelligence and buffering capabilities at the access stations can potentially reduce the number of recirculations and, hence, increase the throughput in the network. Also, adding buffering in the network allowed for many-to-one and one-to-many communication. We showed that the use of an electronic ATM switch at each access station provided the necessary cell-by-cell wavelength translation function (required by Models 2 and 3) along with the added benefits of processing and buffering. We suggest using this type of modeling to study the tradeoffs associated with introducing multicasting at the electronic or the optical layers. Also, the techniques developed here can be used to analyze the performance of all-optical packet/cell switched networks [16] in which optical processing techniques are used for routing packets/cells.

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