FDL Design in Time-Wavelength Switched Optical Networks

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Abstract—An all-optical approach to reduce the speed mismatch between electronic sources and high-speed wavelength channels is to time-division multiplex low-capacity circuits onto each wavelength, and switch time-wavelength-slots within the network. In such a Time-Wavelength-Switched Network (TWSN), fiber delay lines (FDLs) and wavelength conversion (WC) can increase the flexibility in connection slot scheduling and decrease the connection blocking probability. In this paper, we examine the impact of various FDL configurations and WC on a crossconnect’s performance by looking at its ability to schedule as many connections as possible from a given traffic matrix. We present several crossconnect architectures and develop graph formulations that can be used to optimally solve the scheduling problem. Using numerical simulation results, we then compare several FDL configurations. Results show that FDL configurations and WC could play an important role in determining performance.

I. INTRODUCTION

As proposed in [1][2], an efficient and all-optical way to improve the bandwidth utilization in circuit switched wavelength routed (WR) networks is to use TDM on each wavelength, and switch time slots at the nodes. In such a Time-Wavelength Switched Network (TWSN), Time-Wavelength-Space Routers (TWSRs) [2] are configured to change their routing pattern on a time-slot basis. Unlike in packet switches, this pattern is pre-determined at connection set-up time.) Fiber delay lines (FDLs) within a crossconnect (TWSR) provide flexibility in slot assignment for connections by changing the position of a slot in an input frame. However, the scheduling algorithms must ensure that two or more connections on the same wavelength do not use the same FDL at the same time.

In this paper, we consider TWSNs and study the impact of the FDL bank configuration in a TWSN crossconnect. Broadly speaking, we address the question: what is the best way to organize a bank of FDLs to get the best performance? To this end, we consider a single crossconnect and study its performance under a variety of typical FDL organization methods that have been used in the literature. Even though we use a circuit-switching context, many papers on optical packet switching using FDLs to resolve contentions are relevant, e.g., [4], [5], [6], [7]. These and other papers in the literature did not focus on the design or analysis of the FDL bank; their main interest was in scheduling packets optimally or analyzing an algorithm’s performance, for a given node architecture. Moreover, to the best of our knowledge, the architectures we present in this paper have not been presented earlier.

Here, we consider an input traffic matrix (of connections) at a TWSN with a given architecture, and address the problem of scheduling the connections optimally. We pose the scheduling problem as a maximum flow problem on a certain graph. The motivation behind using maximum flow was that it can easily incorporate FDL feedback and wavelength conversion capabilities (limited/full range). Although feedback eases scheduling, multiple traversals through an FDL could cause severe signal degradation, and must be avoided. To address this problem, we also propose a heuristic algorithm for comparing the effects of having limited feedback to the case of infinite feedback.

The rest of the paper is organized as follows. Section II describes the crossconnect architectures. In Section III, we present the model formulations for the different architectures and also present the heuristic algorithm (First Fit). In Section IV we present the simulation results, and finally conclude the paper in Section V.

II. CROSSCONNECT ARCHITECTURES

In this section we present the crossconnect (OXC) architectures that we study in this paper:

1) No Feedback, No Wavelength Conversion
2) With Feedback, No Wavelength Conversion
3) No Feedback, With Wavelength Conversion
4) With Feedback, With Wavelength Conversion

We consider the above cases for FDLs dedicated to each output link. There are various ways in which we can implement the OXC’s, e.g., by using splitters and couplers or by using space division switches. We use the latter approach. We consider K wavelengths per input fiber (λ_i to λ_K) and use the same notion of conversion distance of a wavelength as in [6], since it is most widely accepted. The set of wavelengths to which a particular wavelength λ_i, can be converted to is bounded by the interval [x, w]: x = max(0, i - dis_{conv}) and w = min(K - 1, i + dis_{conv}), where dis_{conv} is the conversion distance.

1) No Feedback, No Wavelength Conversion: The architecture is shown in Fig. 1. It has N input/output fibers, each of which has K wavelengths. The Add/Drop switches are used to terminate a connection if the current node is its destination. The intermediate stage comprises K switches (one

1This concept is similar to TWIN used in [3], but TWIN does not use slot switching within the network.
per wavelength) of size $N \times N(D+1)$. For each of the $N$ outputs, we assign, $(D+1)$ output ports in the FDL stage. Doing so allows a connection to use any of the $(D+1)$ FDL’s (with values $d_0, d_1, \ldots, d_D$). Note that $d_0$ implies that the connection is directly switched to the output fiber (no FDL usage). The connections on different wavelengths, intending to go on the same output fiber are then multiplexed together depending on the FDL chosen. The signals at the FDL outputs are then combined and sent to the output fiber. Note that each FDL output signal may contain multiple wavelengths because several wavelengths may use the same FDL at the same time. The scheduling algorithm, of course, must ensure that the WDM signals at two different FDL outputs (for a given output fiber) do not contain the same wavelengths at the same time. In other words the scheduling algorithm assigns different slots to different connections on the same wavelength, exiting the same output fiber.

2) With Feedback, No Wavelength Conversion: As shown in Fig. 2, to incorporate feedback the FDL channels are demultiplexed and fed to a $1 \times 2$ switch. Doing so allows the connections to be either sent out to the output fiber or be fed back to the intermediate stage switch if they desire another feedback operation. Note that the intermediate stage switch is of dimension $N(D+1) \times N(D+1)$, $(ND$ feedback links and $N$ inputs from previous stage). The stages prior to the intermediate stage are same as in Fig. 1.

3) No Feedback, With Wavelength Conversion: As shown in Fig. 3, to incorporate wavelength conversion we use a bank of $1 \times K$ switches, which direct the incoming connection to the appropriate intermediate switch (of dimension $NK \times N(D+1)$) after wavelength conversion. The stages after the intermediate stage are the same as that of Fig. 1.

4) With Feedback, With Wavelength Conversion: The architecture is shown in Fig. 4 for only one output fiber. All stages prior to the intermediate stage are the same as in Fig. 3. The feedback architecture is similar to that in Fig. 2, only with the addition of wavelength conversion. The FDL channels after being demultiplexed, are fed to a wavelength converter. The output of the converter is fed to a $1 \times K$ switch, which directs the connection to the appropriate intermediate stage switch.

### III. MODEL FORMULATION

In order to analyze the performance of the various architectures, we assume that we are given a traffic matrix consisting of $K \times M$ connections (since there are $K$ wavelengths and $M$ slots per output frame). These connections are assumed to be assigned random slots in the input-wavelength-slot space. Note that since there is no sharing of FDLs and WCs among different links, we can consider the different output links to be independent, and focus on one output frame. An example input traffic matrix is shown in Fig. 5.

Our goal is to schedule these connections optimally (i.e., as many as possible) with the given OXC architecture. We note that this is only one possible way of analyzing the OXC’s performance. Other possible ways include considering dynamic traffic (say Poisson) and using a blocking probability metric [8]. In what follows, we present a solution to the scheduling problem by formulating a maximum flow problem on a graph corresponding to each architecture. This obviously
leads to an optimal scheduling algorithm.

A. Graph Formulation For Architectures (1) and (2)

As shown in Fig. 6 the graph is a bipartite graph with the left vertices representing the incoming time slots of the connections ($T_i$), and the right vertices being the outgoing time slots that the connections are scheduled to go at ($O_j$). We spatially separate the connections, depending on the wavelength on which they enter the switch. The outgoing time slot of a connection $j$, is governed by the time slot at which it enters the switch $i$ and the value of the FDL it takes:

$$j = (i + d_{val}) \mod M \quad \forall \, i, j = 1, 2, 3, ..., M,$$

(1)

where $d_{val}$ is the delay of the FDL used. The links from the source node ($S_o$) to the left vertices indicate the presence of a connection at that time slot. The capacity of the link represents the number of connections present at the corresponding time slot and wavelength. The links from $T_i$ to $O_j$ ($\forall \, i, j = 1, 2, 3, ..., M$) are determined by the use of (1). We will call these links as FDL routes. While scheduling the connections we should make sure that: (a) No two connections on the same wavelength use the same FDL at the same time slot, and (b) for each output frame, at most one connection is scheduled per slot per wavelength. We address these issues by assigning unique values to the links in the graph. The feedback links (the curved dashed lines in Fig. 6), are assigned a capacity of $D$ (no. of FDL’s), since at any given time slot, we can have at most $D$ connections requesting a feedback operation. For Architecture (1) we omit the feedback links. It is easy for the reader to now verify that a maximum flow solution for this graph (from $S_o$ to $D_o$) is a feasible and optimal schedule.

B. Graph Formulation For Architectures (3) and (4)

As shown in Fig. 7, the input stage is represented by a dotted ellipse (time slot), each having $K$ nodes in it. The capacities of the links in the wavelength conversion stage is $N$ (inputs) since at a given time slot we can have at most $N$ connections on a particular wavelength entering the switch. The reader can again verify that a maximum flow solution for this graph (from $S_o$ to $D_o$) is an optimal schedule.

C. Heuristic for Limited Feedback

When the number of feedbacks to the FDL is limited, we do not have a max-flow formulation for the optimal solution. We therefore present a First-Fit heuristic, which solves the flow problem on each slot, one by one. The model formulation is shown in Fig. 8 for one wavelength. The other wavelengths can be obtained by replication. Also, we have allowed a connection to have at most two feedback operations in the figure (the two stages). This can be easily extended to other cases. The links in both stages are determined by the use of (1). The First Fit algorithm has $M$ iterations. At iteration $i$, it schedules (if it can) the connections at input slot $T_i$. In Fig. 8 we show an instance of the algorithm when it is scheduling the connections that have arrived at slot 2 ($T_2$). As shown, there are 2 connections at the input, but only one is scheduled since the link from $T_2$ to $I_2$ cannot be used as the link from $I_2$ to $O_2$ was used in the previous iteration ($i = 1$). The connections scheduled at time slot $T_1$ are represented by bold arcs.

We present a pseudo code of the First Fit algorithm below. A few notations used in the algorithm are:

1) $cap(i, j)_k$ : Capacity of link from node $i$ to node $j$ in the $k^{th}$ iteration.
IV. SIMULATION RESULTS

We consider an OXC with \( N = 8, M = 64 \), and \( K = 8 \) or 16. We generate 10000 input traffic matrices (with \( K M \) connections per matrix located randomly, as described earlier) and look at the drop probability (defined as the fraction of connections that cannot be scheduled). In order to study the impact of various FDL configurations, we consider the following four FDL configurations (some of which are commonly found in the literature) assuming that there are \( D \) FDLs: (a) Series – FDLs have delay values \( \{1, 2, 3, \ldots, D\} \); (b) Odd – FDLs have delays \( \{1, 3, \ldots, 2D - 1\} \); (c) Even – FDLs have delays \( \{2, 4, \ldots, 2D\} \); and (d) Fibonacci – FDLs have delays \( \{1, 2, 3, 5, \ldots, F_D\} \), where \( F_D \) is the \( D \)th Fibonacci number. All delays are in terms slots. We have also evaluated the Geometric configuration (with delays \( 2^0, 2^1, \ldots, 2^{D-1} \)) but don’t present results here because its performance fell in between the others’. Fig. 10 shows the comparison between different configurations of FDLs for the first case. Notice that the Odd configuration performs much better than the Even.

In Fig. 11, we show the effect of having FDL feedback on scheduling. We show results for the Odd and Even cases, which are the extreme cases of Fig. 10. We show the performance of all the four architectures for the Even configuration in Fig. 12. It is seen that having the provision of wavelength conversion and feedback gives the best results as expected. The results of limited feedback (for the First Fit algorithm) are shown in Fig. 13. It is seen that when we limit the number of feedback operations to \( K = 2 \) or 3, the performance is close to that of infinite feedback. This also points to the efficiency of our heuristic. We conclude by comparing the effects of partial and full wavelength conversion capabilities, shown in Fig. 14. A \( d_{\text{conv}} = 3 \) achieves similar results to full wavelength conversion capability (\( d_{\text{conv}} = 15 \) for \( K = 16 \)).
V. CONCLUSIONS AND FUTURE WORK

In this paper, we considered the problem of FDL configuration evaluation in TWSNs. We posed the problem of slot scheduling as a maximum flow problem on a certain developed graph. We presented different architectures to incorporate the provision of having feedback and wavelength conversion. We looked at the drop probability of connections for different FDL configurations and noticed that the Odd configuration performs significantly better than the Even configuration. A heuristic algorithm was presented for the case of having limited number of feedback operations. We showed that the algorithm achieves good results and also verified the performance of having partial wavelength conversion capability. Future work can consider other FDL configurations and aim at designing optimal FDL configurations for specific traffic patterns.

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