Defragmentation of Transparent Flexible Optical WDM (FWDM) Networks

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Abstract: We introduce the network defragmentation problem for FWDM networks, formulate it, and propose heuristics. The network defragmentation process consolidates the available spectrum significantly while minimizing the number of interrupted connections.

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1. Introduction

The Flexible optical WDM (FWDM) network supports channels operating at heterogeneous line rates by allocating spectral resources in a flexible and dynamic manner [1]. In the FWDM network, the channel spacing and channel center frequency are not fixed on standard ITU-T grids, leading to higher spectral efficiency. Additionally, the spectrum in the FWDM network may be dynamically allocated to support dynamic traffic demands. While establishing channels for connections in a FWDM network, the control plane must follow (1) the wavelength continuity constraint, which is defined as the allocation of the same wavelength on each fiber link along the route of a channel, (2) the spectral continuity constraint, which is defined as allocation of the same continuous spectrum on each fiber along the route of a channel, and (3) the spectral conflict constraint, which is defined as non-overlapping spectrum allocation to different channels on the same fiber. Upon tear down of connections, allocated spectral resources are released for future requests. In a dynamic traffic scenario, this channel setup and tear down processes leads to fragmentation of spectral resources. The spectral efficiency in the network is compromised due to the fragmentation of the available spectrum into small noncontiguous spectral bands, decreasing the probability of finding sufficient contiguous spectrum for a connection. New arrival of requests are then either forced to utilize more spectrum in the network or blocked in spite of sufficient spectrum being available. Additionally, as the network evolves, a current optimal routing scheme might no longer provide the optimal spectral utilization over time. There is an increasing demand from the network operators to be able to periodically reconfigure the network and return it to its optimal state, so that the network can operate more efficiently [2]. This operation is defined as network defragmentation. Besides reducing the blocking by consolidating the available network resources, this operation will also enable better network maintenance and more efficient network restoration and bandwidth adjustment.

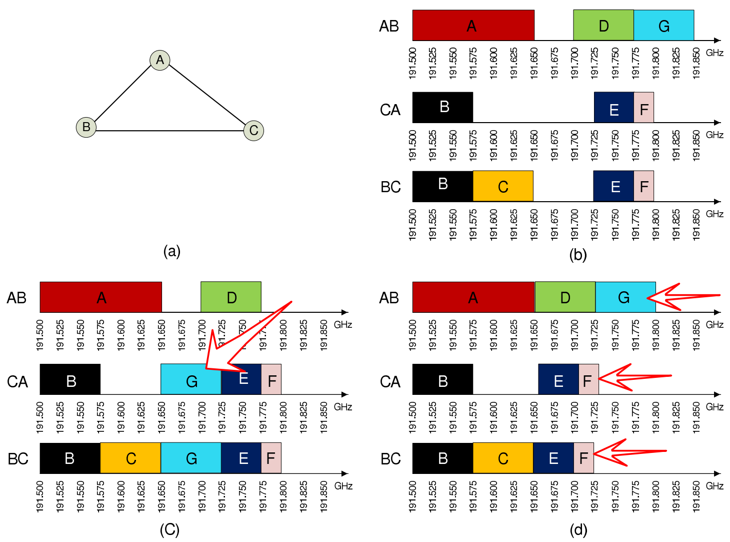
Unlike SONET defragmentation where each fiber is defragmented independently using a time slot interchange technique [3], defragmentation in the WDM network layer requires the entire network to be considered simultaneously. Also, in conventional WDM networks, only the wavelength continuity constraint is required to be maintained while defragmenting the network [4]; however, since the channel spacing in the FWDM network is not constant and WDM channel center frequencies are not fixed on standard ITU-T grids, the defragmentation operation in FWDM networks requires that additional constraints be observed, namely spectral continuity and spectral conflict constraints.

In this paper, we introduce the network defragmentation problem for FWDM networks for the first time. We formulate the problem as an integer linear program and propose two heuristic algorithms, namely, the Greedy-Defragmentation algorithm and the Shortest Path-Defragmentation algorithm.

2. The FWDM Network Defragmentation Problem

In a FWDM network, the available fragmented spectrum bands can be consolidated by reconfiguring existing connections by either changing routes, assigning different wavelengths, or both while maintaining wavelength continuity, spectral continuity, and spectral conflict constraints. However, one of the key operational requirements is to minimize the number of interrupted live connections during the reconfiguration of the FWDM network.

For example, consider a 3-node network as shown in Fig. 1-(a), with the current state of the network as shown in Fig. 1-(b). Assume that the fiber links are bi-directional. Figure 1-(c) and 1-(d) are two possible solutions in which the available spectrum is consolidated by packing the existing requests as much as possible towards the lower wavelengths. In 1-(c), request G can be rerouted on path B-C-A since both fiber link (B, C) and (C, A) have sufficient continuous spectrum (75 GHz) available at the same wavelength 191.65 GHz. However, the same connection cannot be routed on the same path at wavelength 191.65 GHz due to the spectral conflict constraint. This process confines the existing



(a) (b) (C) (d)

Fig. 1. Illustrative Example.

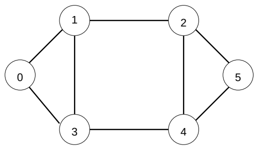


Fig. 2. 6-node Mesh Topology

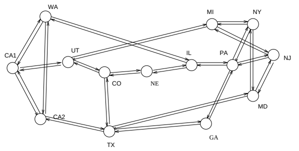


Fig. 3. 14-node NSFNETS

connections within 300 GHz. Figure 1-(d) shows another solution in which requests D, G, E, and F are shifted to lower wavelengths without changing their routes. This process also confines the existing connections within 300 GHz; however the number of interruptions in the first solution (Fig. 1-(c)) is only one, while in the second solution (Fig. 1-(d)) is four. Thus the solution in Fig. 1-(c) is better than the solution in Fig. 1-(d).

The network defragmentation problem in FWDM networks is defined as follows. We are given a physical network, $G(\mathbf{V},\mathbf{E})$, where $\mathbf{V}$ is a set of ROADM nodes, and $\mathbf{E}$ is a set of fibers connecting ROADM nodes. The network supports a set of line rates, $\mathbf{L}$. For example, $\mathbf{L}$={10 Gb/s, 40 Gb/s, 100 Gb/s, 400 Gb/s, 1 Tb/s}. Each line rate $l \in \mathbf{L}$ requires x_l amount of spectrum. For example, a line rate 100 Gb/s requires 50 GHz spectrum. The current network state information, $E^{sd}_{wl} \in \{0,1\}$ is given in which $E^{sd}_{wl} = 1$ represents a connection between source node s and destination node d operating at line rate l, and wavelength w, and $E^{sd}_{wl} = 0$ represents that there is no such connection. The problem is how to reconfigure the existing connections such that the consolidation of available spectrum is maximized while minimizing the number of interrupted connections. We assume that the transponders are wavelength tunable, and established connections are all-optical. In this initial study, we omit the impairment constraints in the network.

The primary objective of the problem is to maximize the consolidation of the spectrum, which is equivalent to minimizing the total required spectrum for the existing connections, and the secondary objective is to minimize the number of interruptions. We formulate the FWDM network defragmentation problem as an Integer Linear Program (ILP) [5], where only primary objective is formulated. We also propose the Greedy-Defragmentation algorithm and the Shortest Path-Defragmentation (SP-Defragmentation) algorithm. To minimize the total required spectrum for the existing connections, we confine the existing connections towards the lower wavelength as much as possible. To minimize the number of interruptions, which can be obtained by reconfiguring connections in descending order of their operating wavelengths (connection with the highest operating wavelength first) on the ascending order of the available wavelengths (on the lowest available wavelength). The Greedy-Defragmentation algorithm is an auxiliary graph based algorithm in which each connection is reconfigured on the lowest available wavelength on any available route with sufficient spectrum. The SP-Defragmentation algorithm reconfigures each connection on the lowest available wavelength along the shortest routes in order to minimize the overutilization of spectrum due to longer routes.

Algorithm 1: Greedy-Defragmentation Algorithm

Step 1: Arrange the existing connections in descending order of their operating wavelength.

Step 2: Pick the first connection from the ordered set and select the lowest wavelength.

Step 3: Construct an auxiliary graph in which a link between a pair of nodes exists if sufficient spectrum is available at a wavelength on a fiber connecting a pair of nodes, otherwise there is no link between a pair of nodes.

Step 4: Find a route with minimum number of hops between the source and destination of a connection.

Step 5: If a route exists, then reconfigure the connection at the selected wavelength on the found route. If no route exists, and the wavelength is lower than the current operating wavelength, then increment the wavelength, and repeat Step 3 to Step 5. If the wavelength is the same as the current operating wavelength of a connection, then do not reconfigure the connection and follow Step 6.

Step 6: Repeat Steps 2 to Steps 5 for all connections in the ordered set.

Algorithm 2: Shortest Path-Defragmentation Algorithm (SP-Defragmentation)

Step 1 and **Step 2**: Same as the Step 1 and Step 2 of the Greedy-Defragmentation algorithm.
Step 3: If sufficient spectrum is available at a wavelength on the shortest path between the source and destination of a connection, then reconfigure the connection at the selected wavelength on the route. If sufficient spectrum is not available and the wavelength is lower than the current operating wavelength of a channel, then increment the wavelength, and repeat Step 3. If the wavelength is the same as the current operating wavelength of a connection, then do not reconfigure the connection and follow Step 4.
Step 4: Repeat Steps 2 and Step 3 for all connections in the ordered set.

3. Numerical Results

We solve the proposed ILP formulations using ILOG CPLEX, and implement a simulator to evaluate the performance of the proposed algorithms. We consider the 6-node mesh (Fig. 2) in which sources and destinations of bi-directional connections are distributed uniformly in the network, and the line rate of a connection is uniformly distributed between 1 Gb/s and 1 Tb/s. The network can support 10 Gb/s, 40 Gb/s, 100 Gb/s, 400 Gb/s, and 1 Tb/s line rates with required spectral width of 25 GHz, 50 GHz, 50 GHz, 75 GHz [6], 150 GHz [7] respectively. We define traffic agility as the ratio of the number of connections tear downs to the total number of connections in the network. We generate various network states by first routing, assigning wavelengths, and allocating spectrum to all requests in the network using the optimal solution proposed in [1], and then randomly removing some of the requests from the found solution.

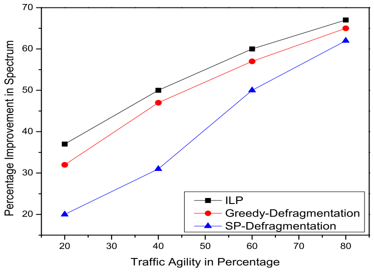


Fig. 4. Spectrum vs. Traffic Agility.

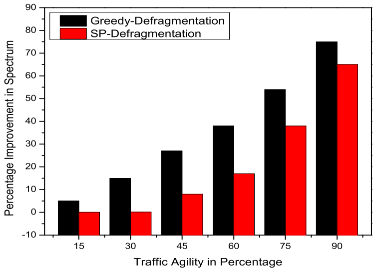


Fig. 5. Spectrum vs. Traffic Agility

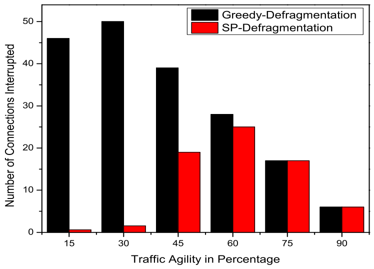


Fig. 6. Interruptions vs. Traffic Agility

Figure 4 compares the performance of the proposed algorithms to the ILP. The Greedy-Defragmentation and SP-Defragmentation algorithms are within 5% and 18% of the optimal solutions. Additionally, as the traffic agility increases the performance of the proposed algorithms approach the optimal solutions. Among the proposed algorithms, the Greedy-Defragmentation algorithm consolidates more spectrum than the SP-Defragmentation algorithm. The reason is that the Greedy-Defragmentation algorithm reconfigures a connection to the lowest available wavelength on any available route, while, in spite of sufficient available spectrum on other routes, the SP-Defragmentation algorithm restricts the reconfiguration of a connection to the lowest available wavelength on the shortest route. Thus, the spectrum required to support the connections routed through bottleneck links in the SP-Defragmentation algorithm is higher than that of any links in the Greedy-Defragmentation algorithm.

Since the ILP is not scalable for large networks, we compare the performance of the proposed algorithms for the 14-node NSF network (Fig. 3) in Fig. 5. The amount of spectrum consolidation in the Greedy-Defragmentation algorithm is higher than that of the SP-Defragmentation algorithm. Additionally, the difference between the spectrum consolidation of the proposed algorithms also increases as the network size increases, which indicates that the Greedy-Defragmentation algorithm is efficient in terms of spectrum consolidation; however, at low traffic agility, the the number of interrupted connections in the Greedy-Defragmentation algorithm is higher than that of the SP-Defragmentation algorithm as shown in Fig. 6. This indicates that the SP-Defragmentation algorithm is efficient in terms of quality of experience. The number of interrupted connections decreases as network becomes more dynamic. The reason is that the number of interrupted connections is a function of the number of left over connections, and the number of left over connections decreases with the traffic agility.

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