Survivable Transparent Flexible Optical WDM (FWDM) Networks

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Abstract: We propose an efficient survivable FWDM network design algorithm for the first time. Survivable FWDM networks are efficient in terms of spectral utilization, power consumption, and cost compared to the conventional survivable fixed grid networks.

OCIS codes: 060.4256 Networks, network optimization; 060.4257 Networks, network survivability

1. Introduction

In a Flexible optical WDM (FWDM) network, spectral resources are allocated in a flexible and dynamic manner [1]. The amount of spectrum allocated to channels may be varied in order to support heterogeneous line rates, and the WDM channel center frequencies may not be fixed on standard ITU-T grids as shown in Fig. 1, leading to higher spectral efficiency compared to conventional fixed grid networks. Furthermore, spectrum in FWDM networks may be dynamically allocated or adjusted to support dynamic traffic demands. Connections can be provisioned dynamically by removing port specific wavelength assignment, port specific routing, and wavelength uniqueness constraints at the existing ROADM nodes. Flexible channels can be set up, torn down, and managed using an automated control plane.

While establishing channels for connections in a FWDM network, the control plane not only must follow the wavelength continuity constraint, which is defined as the allocation of the same wavelength on each fiber link along the route of a channel, but must also follow the spectral continuity constraint, which is defined as the allocation of same continuous spectrum on each fiber along the route of a channel, and the spectral conflict constraint, which is defined as non-overlapping spectrum allocation to different channels on the same fiber. Provisioning survivability for such high line rate channels is an essential requirement. Among network survivability schemes, connection recovery through protection, in which back up network resources are provisioned in advance for each connection, is preferred due to its quick recovery time. A survivable routing and frequency slot assignment algorithm for a ring network is proposed in [2]; however, the proposed solution is not applicable to any generalized network. To the best of our knowledge, there is no prior work on provisioning protection in FWDM networks with generalized network connectivity.

In this paper, we address the survivable FWDM network design problem. For a given physical network topology, a set of requests, a set of line rates offered by the FWDM network, and corresponding minimum required spectrum for each line rate, the FWDM network design problem is how to find routing, wavelength assignment, and spectrum allocation of all-optical working and backup connections such that the required spectral resources are minimized. In this paper, we propose an efficient polynomial-time survivable FWDM network design heuristic.

2. The Survivable FWDM Network Design Problem

Due to additional spectral continuity and spectral conflict constraints, protection in FWDM networks is more challenging than in fixed grid networks. The all-optical working and backup connections must be routed through link disjoint physical paths under wavelength continuity, spectral continuity, and spectral conflict constraints. In order to alleviate the cost of the network, we consider the sharing of transponders among the working and backup connections, and in order to alleviate the connection switching time from working to backup connections, we assume that both working and backup connections must operate on the same wavelength. Thus, the backup connection must operate at the same line rate and at the same wavelength as the working connection, but must be routed on a link-disjoint path.

We first introduce some terminology in order to explain the proposed solution. We assume that the spectrum is discretized in the frequency domain in order to reduce the complexity of the survivable FWDM network design problem. The smallest unit of a spectrum is referred to as a wavelength slot. The spectrum is slotted in such a way that the required spectrum by any line rate is an integer multiple of wavelength slots. We assume that the control plane is aware of the wavelength slot availability information, which is referred as the spectrum availability information.

For example, consider the 6-node network as shown in Fig. 2. The numbers on each link represent the available wavelength slots, each with spectral width of 25 GHz. If a traffic demand R requests a survivable connection with line rate 400 Gb/s from node B to node F, then the working connection can be set up on route $B-D-F$ using a set of wavelength slots $\{4, 5, 6\}$ (400 Gb/s requires a spectral width of 75 GHz [3]). There are two potential link-disjoint

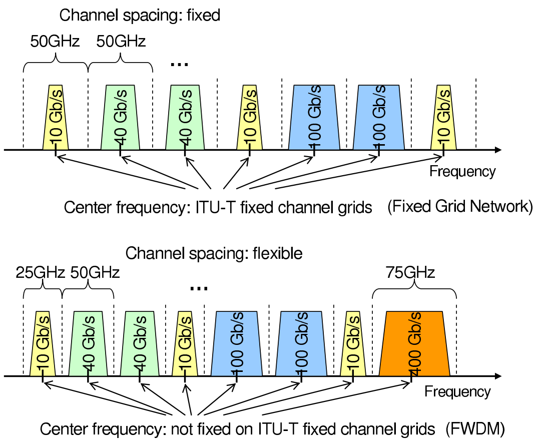

Fig. 1. FWDM Networks vs. Fixed Grid Networks

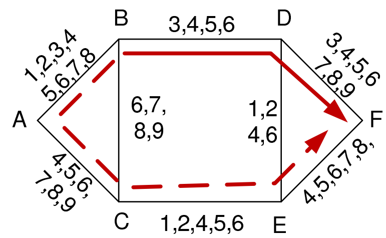

Fig. 2. Illustrative Example.

routes to the working connection. The first route, $B-C-E-F$, cannot be used for the backup connection because, in spite of having sufficient spectral resources on links (B,C), (C,E), and (E,F), the wavelength and spectral continuity constraints are violated. The second route, $B-A-C-E-F$, can be used as the backup connection since the available spectral resources are not only obeying the wavelength continuity, spectral continuity, and spectral conflict constraints, but also available on the same wavelength as the working connection. The survivable FWDM network design problem can be described in detail 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 set of traffic demands, $\mathbf{\Lambda}$ is given in which the request, $R(s,d,l)$, is defined as a survivable connection between source node s and destination node d, operating at line rate l. The problem is how to route, assign wavelengths, and allocate spectrum to working and backup connections of a traffic demand such that the total required spectrum is minimized. We assume that the transponders are wavelength tunable and are shared between working and backup connections. The working and backup connections are all-optical and operate at the same wavelength and same line rates. In this initial study, we omit the impairment constraints in the network.

The survivable FWDM network design algorithm finds survivable wavelength connections for each request $R \in \Lambda$ using an auxiliary graph based approach. Starting at each wavelength slot, an auxiliary graph $G^{'}(\mathbf{N},\mathbf{A})$ is established in which $\mathbf{N}$ represents a set of auxiliary nodes, and $\mathbf{A}$ represents a set of auxiliary links. Starting from the first wavelength slot, if $\lceil \frac{x_l}{\delta} \rceil$ number of consecutive wavelength slots (equivalent to the required spectrum by the line rate l) are available on a link, then an auxiliary link is established on the auxiliary graph, otherwise the auxiliary link is not established. After constructing an auxiliary graph, we find two link-disjoint routes in the auxiliary graph using Suurballe's algorithm. The shorter route is used for the working connection, and the longer route is used for the backup connection. If two link-disjoint routes exist, then we consider these route as a potential solution. We increment the wavelength slot, and repeat the same procedure until we obtain K solutions for each request. Thus, the algorithm finds K different solutions at K different wavelengths. Finally out of K solutions, a solution is selected in which the total route length of the working and backup connection is minimum.

In the following pseudocode of the survivable FWDM network design algorithm, M_e represents the state of the auxiliary link, which is 1 if the link $e \in \mathbf{E}$ is available, and 0 otherwise. The discrete spectrum availability information is denoted by Z_e^w, which is 1 if the wavelength slot w is available on edge $e \in \mathbf{E}$, and 0 otherwise. $W = |\mathbf{\Lambda}| \times \max_l \lceil \frac{x_l}{\delta} \rceil$ represents the total number of given wavelength slots, where δ is the spectral width of a wavelength slot. The routes for the working and backup connections can be obtained by Suurballe algorithm, which is denoted as $Suurballe(G(\mathbf{N},\mathbf{A}),s,d)$, and which returns the working and backup routes of a connection in terms of sets of edges. A set of edges on the working path of the i^{th} solution is denoted as $\mathbf{P}_i$, and the backup path is denoted as $\mathbf{Q}_i$. The operating wavelength of the i^{th} solution of a survivable connection is denoted as θ_i. K denotes the number of solutions, and I, $\mathbf{p}$, and $\mathbf{q}$ are temporary iterators.

3. Numerical Results

We simulate the proposed algorithm on the 14-node NSFNET network. We assume that sources and destinations of 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 in multiples of 1 Gb/s. The network can support 10 Gb/s, 40 Gb/s, 100 Gb/s, 400 Gb/s, and 1 Tb/s

Algorithm 2..1: ALGORITHM(R, Z_e^w, W, K)

$n \leftarrow 1$
while $j \le K$ *and* $n \le W$
do
  for each $e \in \mathbf{E}$
    do $\{M_e \leftarrow 0$
  $I \leftarrow 1$
  for each $e \in \mathbf{E}$
    do
      for $j \leftarrow n$ **to** $n + \lceil \frac{x_l}{\delta} \rceil$
        do
          if $Z_e^j \times I = 1$
          then $\{I \leftarrow 1$
          else $\{I \leftarrow 0$
      if $I = 1$
      then $\{M_e \leftarrow 1$
  $\{\mathbf{p}, \mathbf{q}\} \leftarrow Surballe(G(\mathbf{N}, \mathbf{A}), s, d)$
  if $|\mathbf{p}| > 0$ *and* $|\mathbf{q}| > 0$
  then
    $\mathbf{P}_j \leftarrow \mathbf{p}$
    $\mathbf{Q}_j \leftarrow \mathbf{q}$
    $\theta_j \leftarrow nj \leftarrow j + 1$

return $(\min_i(\mathbf{P}_i,\ \mathbf{Q}_i,\ \theta_i)$

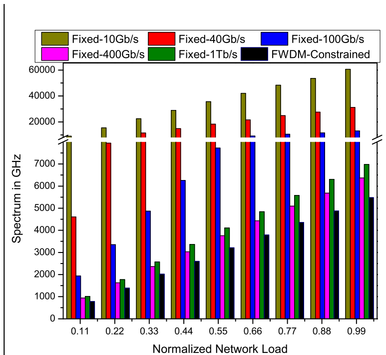

Fig. 3. Spectrum vs Load.

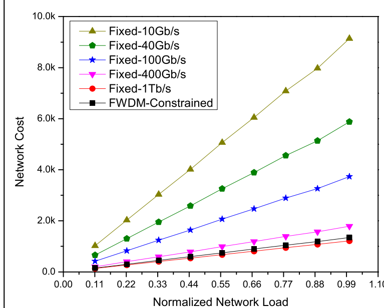

Fig. 4. Cost vs Load.

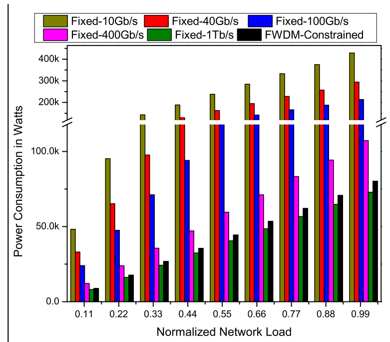

Fig. 5. Power vs Load.

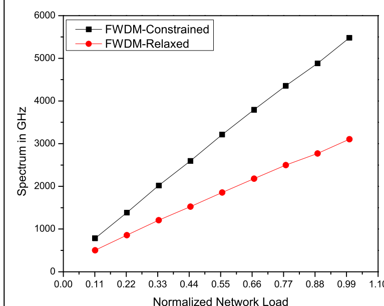

Fig. 6. Constrained vs Relaxed Protection.

line rates with required spectral widths of 25 GHz, 50 GHz, 50 GHz, 75 GHz [3], 150 GHz [4] respectively. The cost of transponders operating at the respective line rates are assumed to be 1x, 2.5x, 3.75x [5], 5.5x, and 6.75x, and the estimated power consumption of transponders operating at the respective line rates are assumed to be 47 W, 125 W, 215 W, 330 W, and 405 W. The spectral spacing, cost model, and energy parameters of 400 Gb/s and 1 Tb/s is obtained by extending the current trend using the logarithmic function. We experimentally determine that $K = 15$ solutions per request are sufficient to reach the steady state.

The required spectrum in survivable fixed grid networks and a survivable FWDM network is compared in Fig. 3. Spectrum utilization in the survivable FWDM network is improved by 91%, 83%, 60%, 16%, and 22% in the worst case compared to the 10 Gb/s, 40 Gb/s, 100 Gb/s, 400 Gb/s, and 1 Tb/s fixed grid networks. The survivable FWDM networks establish connections at any line rate by allocating variable amount of spectrum, and thus minimizes the over-provisioning of spectral resources to connections. Additionally, for higher data rate demands, establishing channels at higher line rates improves spectral efficiency. Since the 400 Gb/s line rate is closest to the average data rate of 500 Gb/s, the performance of the survivable 400 Gb/s fixed grid network is the closest to that of the FWDM network.

We also observe significant improvement in cost and power consumption of the survivable FWDM network compared to the survivable fixed grid network as shown in Fig. 4 and 5. The cost and power consumption in the survivable FWDM network is improved by at least 81%, 72%, 63%, and 24% compared to the 10 Gb/s, 40 Gb/s, 100 Gb/s, and 400 Gb/s fixed grid network. The cost and power consumption of the survivable FWDM network is increased by at most 11% compared to the 1 Tb/s fixed grid network. The reason is that the required number of transponders, cost per unit capacity, and power consumption per unit capacity of the 1 Tb/s network is minimum.

If we relax the constraint of having the same operating wavelength in both working and backup connections, by either installing dedicated transponders for both working and backup connections, then we observe between 35% and 43% improvement in the spectral efficiency compared to the constrained survivable FWDM network as shown in Fig. 6; however the network cost is double that of the constrained survivable FWDM network cost.

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