

# Energy-Efficient Survivable Grooming in Software-Defined Elastic Optical Networks

Jingjing Wu, Zhaolong Ning, and Lei Guo

**Abstract**—Survivability in the OpenFlow based software-defined elastic optical networks (SD-EONs) is more challenging than that in the conventional optical networks because failures can affect control plane operations. Meanwhile, traffic grooming enabled by sliceable transponders can reduce power consumption and obtain higher spectrum efficiency. In this paper, we study the survivable grooming routing and spectrum allocation (SG-RSA) in SD-EON. We first provide an integer linear programming (ILP) formulation to minimize both the required transponders and the maximum number of occupied frequency slots. Then, we develop a heuristic algorithm called shared backup path grooming protection (SBPGP) to get enough protection and less resources consumption. Extensive simulations are performed to study the power consumption of optical elements in data plane. Numerical results show that the proposed SBPGP scheme achieves better performances than the traditional shared backup path protection (SBPP) without grooming.

**Index Terms**—Software-defined, Survivability, Elastic optical network, Traffic grooming, Energy efficiency

## I. INTRODUCTION

In recent years, traffic growth results capacity upgrades in telecommunications networks, especially in metro or core networks. As a result, 100Gb/s optical transport systems have been widely deployed, and 400Gb/s and 1Tb/s super-channels have been demonstrated in laboratories and field trials[1]. However, conventional optical transport networks based on Wavelength Division Multiplexing (WDM) are challenged due to its inflexible grid and coarse bandwidth granularity. In order to make better use of optical resources to accommodate the ever-increasing new internet applications such as Internet Protocol Television (IPTV), video on demand and cloud computing applications, spectrum efficient Elastic Optical Network (EON) based on Orthogonal Frequency Division Multiplexing (OFDM) technology has been proposed as new network architecture[2-4]. Compared to traditional WDM networks, EON is able to provide arbitrary contiguous frequency slots that vary from sub-wavelength to super-wavelength bandwidth granularity in an efficient way. In

an EON, the spectrum assigned to a lightpath does not strictly follow the International Telecommunication Union (ITU-T) recommendation central frequency and grid. Traffic demand is accommodated with a variable number of frequency slots, and guard bands between two adjacent lightpaths are assigned for optical filter consideration.

In optical networks, enormous data loss may be experienced in the event of network failures, such as node, link, or channel faults. This problem becomes more compelling when lightpaths are migrated to high bit rates as the EON continues being mature. Survivability is more sophisticated in EON than that in WDM networks since several OFDM channels can be optically aggregated into super-channels, which will affect a larger number of connections. Thus, reliability has become an issue of great interest in the design of elastic networks, and has been intensively studied in many literatures [6,10-12]. In general, survivability is one of the basic requirements of a network, both in traditional WDM networks and EON.

In these years, software-defined networks (SDN) has got a lot of research attentions. By decoupling the control and data planes of a network, SDN makes the network programmable, adaptive and application aware[5]. To support software-defined EONs, an open standard protocol such as the OpenFlow (OF) has been included to facilitate software-defined routing, switching, and network management. According to OpenFlow, the controller can configure the forwarding table in the OpenFlow switches and get the flow statistic information. With these network information, it is shown that the SDN has the potential to optimize the EONs.

Another serious problem in SD-EON is energy consumption. According to an up-to-date survey, the energy consumption of global networks accounts for about 8% of the total energy consumption, and the proportion will reach up to 20% by 2020[7]. An SD-EON supports various data rates (including sub-wavelength and super-wavelength services) through bandwidth-variable transponders (BVT) at the network edge and bandwidth-variable optical cross-connects (BV-OXCs) in the network core[8]. However, carrying each traffic demand using an exclusive BVT might not be cost-efficient, especially for sub-wavelength services. Since increasing the number of optical channels increases the optical power injected in optical links, which may not be acceptable for the future development of networks. Traffic grooming is regarded as an effective method for power saving by using fewer transponders and, by avoiding the need of additional guard bands. Survivable traffic grooming that addresses both grooming provisioning and

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survivability seeks to provide survivable capability for traffic demands and minimize the consumption of spare capacities in the network. By combining energy efficient design with survivable traffic grooming technique, which groups several wavelength-level lightpaths into one super-wavelength level lightpath to be switched by one port and thus utilizes the network resources effectively, previous work remains a relatively unexplored issue and gains much attention recently.

In this paper, in order to well address the energy-efficient survivable optical network, we study the Survivable Grooming Routing and Spectrum Allocation (SG-RSA) problem in software-defined elastic optical networks. As an analogy to the Routing and Wavelength Assignment (RWA) problem in WDM optical networks, the SG-RSA problem is also proved NP-hard[9]. We present ILP formulation for the SG-RSA problem, which can provide protection for traffic demands by optimally allocating the frequency slots in the network. We then propose a heuristic algorithm called Shared Backup Path Grooming Protection (SBPGP) to get enough protection and less resources consumption for the dynamic traffic demands. Compared with previous protection algorithm, SBPGP can obtain better performances in resource utilization ratio and power efficiency.

The rest of this paper is organized as follows. Related work is reviewed in Section II. Then, problem statement is addressed in Section III. The ILP formulation is developed in Section IV and the related heuristic algorithm is proposed in Section V. Thereafter, simulation results are analyzed in Section VI. Finally, we conclude the paper in Section VII.

## II. RELATED WORK

This section discusses the main works that have been cited in the preceding section.

For the survivability issue in EON, the authors of [10] formulated the joint multilayer planning problem and presented two ILP formulations to solve it. The authors of [11] proposed a novel mutual backup model to improve the survivability of the control plane in software-defined EON. The authors of [12] provided the survivability to two types of traffic demands: unicast and anycast. To provide network survivability, the authors split a demand into a number of routing paths if the paths' combination guarantees the realization of a specific demand volume in the case of a single link failure. The authors of [13] took the advantages of failure-independent path protecting preconfigured cycles (FIPP p-cycles) and investigate how to realize spectrum efficient resilience design with them. The authors of [14] introduced a new survivable multipath provisioning scheme (MPP) that efficiently supports demands with flexible protection requirement and studied the survivable multipath routing and spectrum allocation (SM-RSA) problem, which aims to accommodate a given set of demands with minimum utilized spectrum.

For the traffic grooming issue in EON, The authors of [15] studied energy-efficient traffic grooming in IP-over-elastic optical networks with a sliceable optical transponder. Three bandwidth-variable transponders were investigated. The authors of [16] proposed two novel network architectures based

on sliceable optical layer and numerically compare them with the traditional packet-over-optical network architecture. The authors of [17] focused on the different node architectures, and compared their performance in terms of scalability and flexibility. The authors of [18] investigated the potential gains by jointly employing traffic grooming and multipath routing in combination with a realistic physical impairment model. The authors of [19] proposed an optically groomed data center network framework.

Many researchers focus on reducing the energy consumption in the optical networks. A detailed survey of approaches reducing energy consumption of core networks is presented in [20]. The authors of [21] introduced a comprehensive study on energy efficiency and network performance enhancement in the presence of tidal traffic. The authors of [22] proposed a software-defined networking scheme for quality of service provisioning through energy efficient assignment of optical transponders, employing bandwidth variable distance adaptive modulation and coding. The authors of [23] presented a novel spectrum allocation algorithm based on spectrum integration. The algorithm reduced spectrum fragmentation by taking the usage of spectrum slots on the neighboring links into consideration. The authors of [24] targeted the reduction of the energy consumption of an IP over WDM backbone network by introducing three novel heuristic schemes.

However, further studies are still necessary on the survivability problem with consideration of the energy efficient constraints. Moreover, few studies have investigated the survivability algorithms that support power saving method in software-defined elastic optical networks.

## III. BACK GROUND

### A. Network Model

Fig. 1. illustrates the six node architecture of an SD-EON, which consists of two separate planes, i.e., the data plane and control plane. The data plane includes the network elements such as bandwidth variable transponders (BVT), optical amplifiers (OA) and optical cross connects (OXC). The control plane consists of an SDN controller and several agents (AGs) commonly using open and standard protocols, such as the OpenFlow protocol (OF-AGs). The SDN controller provides a method for programmatic control of network resources and simplification of the control plane process. Each OF-AG attaches to a network element locally and controls the operation for data transfers. By deploying the control plane intelligence in the controller, resources allocated in hardware nodes for control plane functions can be reduced.

The network topology is defined as  $G(N, L)$  for an optical mesh network, where  $N$  is the set of nodes, and  $L$  is the set of fiber links which is bidirectional and contains two unidirectional fibers with contrary direction. Let  $TD$  denote the set of traffic demands. The  $r^{th}$  traffic demand is denoted as  $td(s_r, d_r, B_r)$ , where  $s_r$  and  $d_r$  ( $s_r, d_r \in N$ ) are the source and destination nodes,  $B_r$  is the bandwidth requirement in Gb/s, we need to provide it with sufficient working bandwidth as well

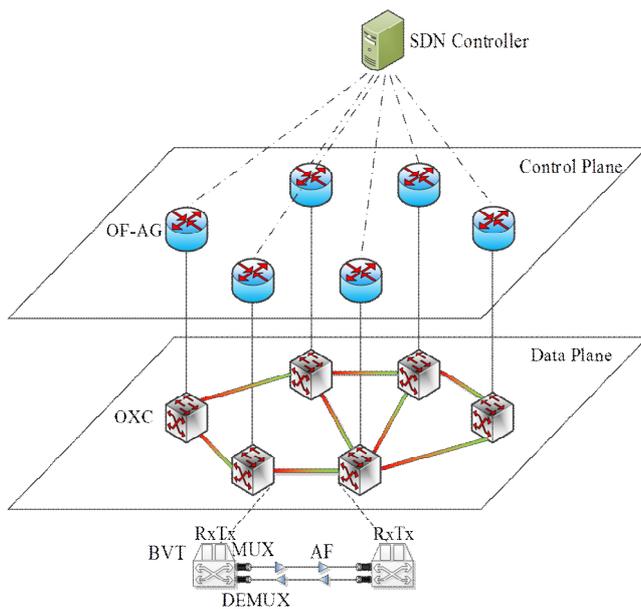


Fig. 1. Network model for an SD-EON.

as satisfying a backup path. In each fiber link an ordered set  $F = \{f_1, f_2, \dots, f_K\}$  of frequency slots is given. Where  $K$  is the maximum number of slots on a link and we assume all links are assigned the same number of slots. The shortest path algorithm, i.e., Dijkstra's algorithm, is applied to compute the route.

### B. Node Architecture

Fig.2. depicts the detailed architecture of an optical node in an SD-EON. It consists of wavelength selective switches (WSSs) on both side of the node. WSSs are widely utilized in present optical nodes. Different technologies such as liquid crystal switches, liquid crystal on silicon, and micro-electro mechanical systems have been used to implement WSSs [25]. The WSS based OXC node architecture has the advantage of modular growth capability in terms of the node scale. The transmitter array shown in Fig. 2 generates  $K$  slots, which can be directed toward different destinations. The bandwidth and bit rate of each slot can be varied at the digital signal processing (DSP) by software, selecting the suitable modulation format and number of active OFDM sub-carriers. Multiple formats per each sub-carrier are supported. The wavelength of the flex-grid channel is set at the tunable laser source. The architecture shows a full north-south integration, including the data plane to be controlled, the OF-AGs that enables the SDN-based configuration, the SDN controller itself, and the application programming interface (API) that communicate the controller with the upper plane. Each OF-AG contains a set of modules that allow the communication between the data plane and the SDN controller. The net information module sets up a local traffic database, where the flow-entries for the lightpaths that use the node is stored. The equipment communication module establishes a connection towards the data plane, providing control and retrieval of optical features. The OpenFlow protocol module establishes an OpenFlow protocol based connection with the controller, performing the particular data

plane features and capabilities. Finally, the SDN controller defines the centralized logic component of this architecture, where the information received from the data plane, through OF protocol messages, is analyzed and exposed to control plane by means of well-implemented APIs. These APIs provide access to optical related data managed by the controller.

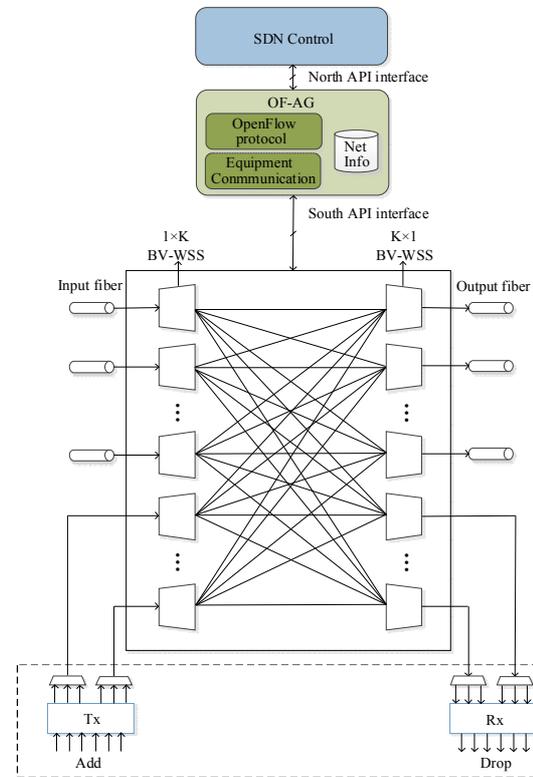


Fig. 2. SDN based OXC node architecture.

## IV. ILP FORMULATION

In this section, we present an optimal ILP formulation for the survivable problem with traffic grooming to minimize the energy consumption in SD-EON.

An example is given in Fig. 3, where a traffic demand  $td(node1, node4, 37.5Gb/s)$  shares backup frequency slots on its backup path  $node1-node9-node4$  with another traffic demand  $td(node10, node1, 25Gb/s)$ . As one frequency slot can carry 12.5Gb/s capacity, one possible backup spectrum assignment is depicted in Fig. 3(b). Suppose that two specific sets of contiguous slots (which are highlighted in the figure in red and blue) have been assigned, one guard band is also assigned for each traffic demand. Note that, the free frequency slots on this lightpath except these occupied slots can be used to accommodate the new traffic demands. Consider the situation that there are two new traffic demands  $td(node6, node5, 50Gb/s)$  and  $td(node3, node4, 50Gb/s)$  require specific accommodation. However, the free frequency slots on link 9-4 are not enough to accommodate both mentioned new traffic demands bandwidth, which is shown in Fig. 3(c). We have to block one traffic demand because there is

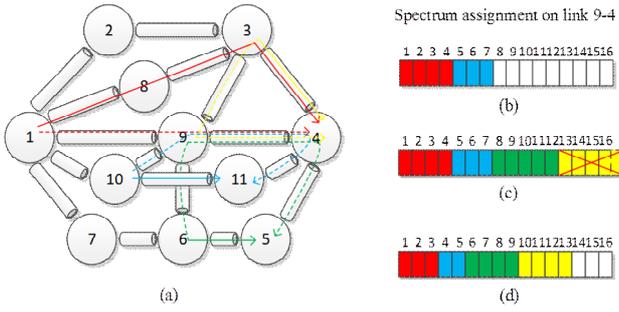


Fig. 3. Illustration of Shared Backup Path Protection

no unoccupied frequency slot for the guard band for traffic demand  $td(node3,node4,50Gb/s)$ . However, after traffic grooming, where the guard band is no longer needed, we can see that the approach in Fig. 3(d) uses fewer transponders and less frequency slots.

The used notations, given parameters and problem statement variables are described below:

$P$ : The set of all lightpaths.

$WP_{td(s_r,d_r,B_r)}$ : The set of working path for traffic demand  $td(s_r,d_r,B_r)$ , where  $WP_{td(s_r,d_r,B_r)} \in P$ .

$BP_{td(s_r,d_r,B_r)}$ : The set of backup path for traffic demand  $td(s_r,d_r,B_r)$ , where  $BP_{td(s_r,d_r,B_r)} \in P$ .

$T_{ij}$ : Number of transponder pairs on lightpath from  $i$  to  $j$ .

$PC_{BVT}$ : The power consumption of BVT.

$PC_{BV-OXC}$ : The power consumption of BV-OXC.

$PC_{OA}$ : The power consumption of OA.

$f_k$ : Slot index, where  $f_k \in F$ .

$x_{i,j}^{f_k}$ : Binary variable. Equal to 1 if slot  $f_k \in F$  on lightpath from  $i$  to  $j$  is allocated to a traffic demand, and equal to 0 otherwise.

$\omega_{s_r,d_r}^{i,j}$ : Binary variable. Equal to 1 if a given traffic demand  $td(s_r,d_r,B_r)$  traverses lightpath from  $i$  to  $j$  in its working path, and equal to 0 otherwise.

$\xi_{s_r,d_r}^{i,j}$ : Binary variable. Equal to 1 if a given traffic demand  $td(s_r,d_r,B_r)$  traverses lightpath from  $i$  to  $j$  in its backup path, and equal to 0 otherwise.

$e_{i,j}$ : Binary variable. Equal to 1 if there exists a lightpath from  $i$  to  $j$ , and equal to 0 otherwise.

$S_{i,j}^r$ : Integer. Denotes the starting frequency slot index of an existing traffic demand  $td(s_r,d_r,B_r)$  via lightpath from  $i$  to  $j$  no matter working path or backup path,  $td(s_r,d_r,B_r) \in TD$ ,  $S_{i,j}^r \geq 1$ .

$E_{i,j}^r$ : Integer. Denotes the ending frequency slot index of an existing traffic demand  $td(s_r,d_r,B_r)$  via lightpath from  $i$  to  $j$

no matter working path or backup path,  $td(s_r,d_r,B_r) \in TD$ ,  $E_{i,j}^r \geq 1$ .

$N_{i,j}^r$ : Integer. Denotes the number of frequency slots allocated to a traffic demand  $td(s_r,d_r,B_r)$  via lightpath from  $i$  to  $j$  no matter working path or backup path,  $td(s_r,d_r,B_r) \in TD$ ,  $N_{i,j}^r \geq 1$ .

$T_a^{i,j}$ : Binary variable. Equal to 1 if lightpath from  $i$  to  $j$  uses transmitter a at node  $i$ , and equal to 0 otherwise.

$R_b^{i,j}$ : Binary variable. Equal to 1 if lightpath from  $i$  to  $j$  uses receiver b at node  $j$ , and equal to 0 otherwise.

Power consumption of BVT depends not only on the number of frequency slots, but also on the modulation format used [8]. Table I presents the power consumption for the transmission and reception of a single frequency slot (with bandwidth 12.5 GHz) for several modulation formats.

TABLE I  
POWER CONSUMPTION OF A BVT FOR THE TRANSMISSION AND RECEPTION OF A SINGLE SUBCARRIER WITH DIFFERENT MODULATION FORMATS

Modulation	TR(Gb/s)	Power Consumption(kW)
BPSK	12.5	112.374
QPSK	25	133.416
8QAM	37.5	154.457
16QAM	50	175.498
32QAM	62.5	196.539
64QAM	75	217.581

Power consumption of BV-OXC is defined as (1):

$$PC_{BV-OXC} = N85 + \alpha 100 + 150 \quad (1)$$

where  $N$  is the node degree and  $\alpha$  is the add/drop degree and 150W is an overhead additional contributions to power consumption. Here, we assume  $N$  and  $\alpha$  are constant for all the nodes.

Power consumption of OA is defined as (2) [27]:

$$PC_{OA} = \left\lceil \frac{d}{80} + 1 \right\rceil \cdot 100 \quad (2)$$

where  $d$  is the link length.

The ILP aims to minimize the total power consumption of the network elements and the number of optical transponders in the network:

$$\text{Minimize: } PC_{BVT} + PC_{BV-OXC} + PC_{OA} + \sum_{i,j \in N} T_{ij}$$

(3)

subject to the following constraints:

$$\sum_{i,j \in N} \sum_{f_k, f_n \in F} (x_{i,j}^{f_k} + x_{i,j}^{f_n}) = 1, \quad \forall n \neq k. \quad (4)$$

$$x_{i,j}^{f_n} - x_{i,j}^{f_{n-1}} = \begin{cases} 0 & n = k, \dots, k + B_r - 1 \\ 1 & n = 1, \dots, k - 1, \quad k = 1, \dots, |K| - B_r, \\ -1 & n = k + B_r, \dots, |K| \end{cases}$$

$$\forall n \neq k, f_n \in F \quad (5)$$

$$\sum_{i,j \in N} (\omega_{s_r, d_r}^{i,j} + \xi_{s_r, d_r}^{i,j}) \leq 1, \forall s_r, d_r \in N, \forall \omega, \xi \in P \quad (6)$$

$$\sum_{i,j \in N} (\omega_{s_r, d_r}^{i,j} \cdot \xi_{s_r, d_r}^{i,j}) \leq 0, \forall s_r, d_r \in N, \forall \omega, \xi \in P \quad (7)$$

Equation (4) avoids frequency slot collision between different traffic demands. Each slot on a link can only be allocated to one traffic demand. Equation (5) is the contiguous frequency slots assignment constraints. Whenever there is a slot  $f_k$  selected as the lowest indexed slot for a traffic demand, the consecutive slots  $f_{k+1}, \dots, f_{k+B_r-1}$  should be assigned to this demand. Equation (6) and (7) guarantee that a given fiber link can be used only by at most one lightpath (working path or backup path) route. And for a given  $td(s_r, d_r, B_r)$ , its working path is link-disjoint with its backup path.

Traffic grooming ILP formulation are designed for different types of situations. As the spectrum resources are large relative to traffic demand load, optical-layer routing and spectrum allocation are simplified to reduce the complexity of the formulation, namely, a range of continuous and contiguous spectrum can always be found for a traffic demand.

#### A. Build a New Lightpath for a Traffic Demand

In this scenario, we assume that the link from  $i$  to  $j$  does not exist in the virtual topology, which implies that no traffic demand can be groomed on that link.

$$\sum_{i,j \in N} \sum_{f_k \in F} x_{i,j}^{f_k} e_{i,j} = 0 \quad (8)$$

$$\sum_{i=s_r} \sum_{a \in T} T_a^{i,j} = 1, \forall i \neq j \quad (9)$$

$$\sum_{j=d_r} \sum_{b \in T} R_b^{i,j} = 1, \forall i \neq j \quad (10)$$

The constraint (8) ensures that, if  $e_{i,j} = 0$ , the link from  $i$  to  $j$  does not exist in the virtual topology, we should build a new lightpath to accommodate this traffic demand. Equation (9) and (10) are the transponder allocation constrains. It ensures that each traffic demand from  $s_r$  to  $d_r$  is mapped to a transmitter-receiver pair.

#### B. Grooming in front of an existing traffic demand

In this scenario, we assume that there exists a lightpath built for the former traffic demand and the remaining spectrum resources in front of the occupied slots are large enough to accommodate a following traffic demand, which is shown in Fig. 4(a).

$$\sum_{i,j \in N} \sum_{f_k \in F} x_{i,j}^{f_k} e_{i,j} = 1 \quad (11)$$

$$\sum_{i \in N} \sum_{a \in T} T_a^{i,j} \leq 1, \forall i \neq j \quad (12)$$

$$\sum_{j \in N} \sum_{b \in T} R_b^{i,j} \leq 1, \forall i \neq j \quad (13)$$

$$\sum_{i,j \in N} \sum_{f_k \in F} x_{i,j}^{f_k} = 0, \text{ where } k = S_r - B_r - 1, \forall f_k \in F \quad (14)$$

The constraint (11) ensures that, if the link from  $i$  to  $j$  exists in the virtual topology,  $e_{i,j} = 1$ . Equation (12) and (13) guarantees that one groomed traffic demand is allocated with a unique transmitter at the beginning of a lightpath or a unique receiver at the ending of a lightpath. Equation (14) is the capacity constrain of the grooming lightpath. It guarantees to grooming the new traffic demand to such lightpath for which there is enough space for the frequency slot assignment.

#### C. Grooming after an existing traffic demand

In this scenario, we assume that there exists a lightpath built for the former traffic demand and the remaining spectrum resources after the occupied slots are large enough to accommodate a following traffic demand, which is shown in Fig. 4(b). In addition to constraints (11), (12) and (13), we have

$$\sum_{i,j \in N} \sum_{f_k \in F} x_{i,j}^{f_k} = 0, \text{ where } k = E_r + B + 1, \forall f_k \in F \quad (15)$$

Equation (15) guarantees that the frequency slots following an existing traffic demand are unoccupied and the bandwidth is large enough with a guard band.

#### D. Grooming in the middle of two existing traffic demands

In this scenario, we assume that there exists a lightpath built for the former traffic demands and the remaining spectrum resources between two occupied slots are large enough to accommodate a following traffic demand, which is shown in Fig. 4(c). In addition to constraints (11), (12) and (13), we have

$$\sum_{i,j \in N} \sum_{f_k \in F} x_{i,j}^{f_k} = 0, \text{ where } k = E_r + B, \forall f_k \in F \quad (16)$$

Equation (16) guarantees that the frequency slots between two existing traffic demands are unoccupied and the bandwidth is large enough without a guard band.

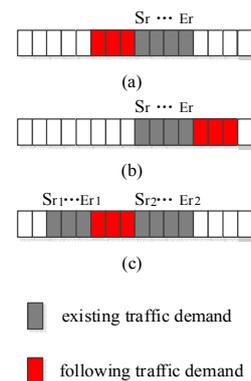


Fig. 4. Illustration of frequency slot allocation

## V. HEURISTIC ALGORITHM

When the network topology is small, the proposed ILP model is tractable. However, for the large scale network, it is widely known that ILP model can not be directly solved in practical time. To achieve the goal of minimizing the maximum number of frequency slots on a fiber and the total number of the transponders, we present a novel heuristic method called

### Shared Backup Path Grooming Protection (SBPGP).

Lightpaths are established by optical layer routing and spectrum assignment. In general, there are four possible grooming roles to accommodate a new traffic demand, as follows.

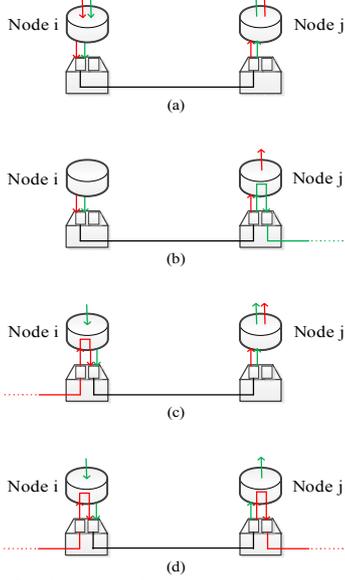


Fig. 5. Illustration of optical grooming

Role 1: The new traffic demand has the same source and destination with an existing lightpath. Groom the traffic demand onto this existing lightpath, shown as Fig. 5(a).

Role 2: The new traffic demand has the same source node but the different destination node with an existing lightpath. Groom the traffic demand onto this existing lightpath partially until the end of the existing lightpath. Then, establish new lightpaths for the other parts of the demand, shown as Fig. 5(b).

Role 3: The new traffic demand has the different source node but the same destination node with an existing lightpath. Establish new lightpaths for the traffic demand at the beginning. Groom the traffic demand onto the existing lightpath with the overlap part, shown as Fig. 5(c).

Role 4: The new traffic demand has the different source and destination with an existing lightpath but it overlaps with the existing lightpath in the middle section. Groom the overlap part onto this existing lightpath partially. Establish new lightpaths for the other parts of the demand, shown as Fig. 5(d).

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#### Algorithm Shared Backup Path Grooming Protection

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**Input:** Physical network topology  $G(N, L)$ ;

Set of traffic demands  $TD$ ;

**Output:** Minimum cost path pair for each traffic demand in the network  $P$ ;

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1. Initialize  $P \leftarrow \phi$ ;
  2. Waiting for the arrival of the traffic demands in  $TD$ ;
  3. **if**  $td(s_r, d_r, B_r)$  is for establishing a connection **then**
  4.   **for** traffic demand  $td(s_r, d_r, B_r)$  in  $TD$  **do**
  5.     Run Dijkstra on  $G$  to compute the working path  $WP_{td(s_r, d_r, B_r)}$ ;
  6.     **if** it is successful **then**
  7.       Groom the traffic demand to an existing working path under the role 1-4;
  8.       **if** the grooming succeeds **then**
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9.       Allocate a set of  $B_r$  contiguous sub-carriers on each link;
  10.      Remove the guard band;
  11.      Update the transponder status;
  12.      **else**
  13.       Build a new working path  $P \leftarrow WP_{td(s_r, d_r, B_r)}$ ;
  14.      Allocate a set of  $B_r + 1$  contiguous sub-carriers on each link;
  15.      Allocate a new transmitter-receiver pair;
  16.      **end if**
  17.      **else**
  18.       Block this traffic demand;
  19.      **end if**
  20.      Run Dijkstra on  $G$  to compute a link-disjoint backup path  $BP_{td(s_r, d_r, B_r)}$ ;
  21.      **if** it is successful **then**
  22.       Groom the traffic demand to an existing backup path under the role 1-4;
  23.       **if** the grooming succeeds **then**
  24.          Allocate a set of  $B_r$  contiguous sub-carriers on each link;
  25.          Remove the guard band;
  26.          Update the transponder status;
  27.          **else**
  28.           Build a new backup path  $P \leftarrow BP_{td(s_r, d_r, B_r)}$ ;
  29.          Allocate a set of  $B_r + 1$  contiguous sub-carriers on each link;
  30.          Allocate a new transmitter-receiver pair;
  31.          **end if**
  32.          **else**
  33.           Block this traffic demand;
  34.          **end if**
  35.       **end for**
  36.      **else if**  $td(s_r, d_r, B_r)$  is for releasing a connection **then**
  37.       Remove the traffic demand from the network;
  38.       Release the consumed resources;
  39.      **end if**
  40. Return  $P$ .
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To satisfy a given set of traffic demands, our algorithm sorts these traffic demands and serves each demand one by one. The detailed procedures of SBPGP are presented as follows.

We also analyze the time complexity of the SBPGP algorithm in a topology with  $N$  nodes. In the SBPGP algorithm, the time complexity is  $O(2 \cdot (N + L \cdot \log L))$  according to [26] where  $N$  is the total number of nodes and  $L$  is the total number of links since we will run two times of Dijkstra's algorithm to compute two link-disjoint end-to-end paths for each traffic demand. Note that in the grooming, routing, and frequency slots assignment procedure of the SBPGP algorithm, we adopt the k-shortest path algorithm, and if there are multiple possibilities (several equal grooming links or available frequency slots for new lightpaths), a First Fit policy is applied for routing and spectrum assignment.

## VI. SIMULATION AND ANALYSIS

In this section, we first present optimal results of ILP formulation in a small topology with a small number of traffic demands. Then numerical results of the heuristic algorithm are given to illustrate its performance in large topology with a large number of traffic demands. Results show that both ILP and heuristic algorithms have the same trend on power consumption with survivable grooming technology.

In simulation, we test the performance of power

consumption and number of transponders. In SD-EON, the power consumption mainly comes from BVT, BV-OXC and OA.

We run ILP formulation on a four-nodes and five equal length links network. We assume the number of frequency slots on each link is enough, that is, the network can provide service for every traffic demand successfully. We propose that each transponder has enough capacity and can launch random subcarriers with a Binary Phase Shift Keying (BPSK) modulation format. From Table II, we can see that when the number of traffic demands becomes larger, the number of consumed slots increases. The number of transponders also shows ascendant trend, but it rises slowly. The reason for this phenomenon is that multiple traffic demand can share a single transponder. Line 4 in Table illustrates the total power consumed by the three network elements. Fig. 6 shows the total power consumption in ILP comparing with the scheme without grooming. We can see that significant power savings are achieved by using grooming technology. The reason is that, grooming can save guard bands between the two neighboring traffic demands, and the number of transponders decreases.

TABLE II  
RESULTS OF ILP

Demands number	2	4	6
Frequency slots	15	32	56
Number of transponders	8	12	14
Power of consumption(kW)	8.264	9.389	10.063

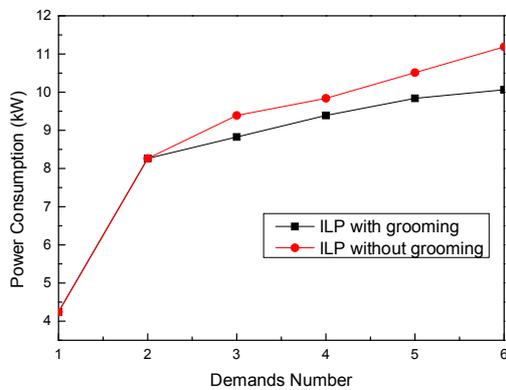


Fig.6. Comparison of power consumption of ILP with and without grooming.

Now we present the results of the heuristic algorithm on the network topology in Fig. 7. The network is 14 nodes and 21 links that are assumed to be bidirectional fibers. Each frequency slot is 12.5GHz. Spectrum widths of 25GHz, 50GHz, and 80GHz carry traffic for 40Gbps, 100Gbps, and 400Gbps line rates with different modulation formats. In our simulation, we consider the incremental traffic model. In this model, each traffic demand enters the network individually and once allocated, traffic demands in the network cannot be reconfigured. If the network resource could not provide service for a traffic demand successfully, the demand will be rejected immediately without waiting in a queue. In simulation, we test

the performances of blocking probability, total port-cost, spectrum utilization ratio and power consumption. Blocking probability is defined as the ratio of the number of blocked demands over the number of arriving demands. Total port-cost is defined as the number of consumed transponders by all accepted traffic demands. Spectrum Utilization Ratio is defined as the ratio of occupied frequency slots over the total frequency slots.

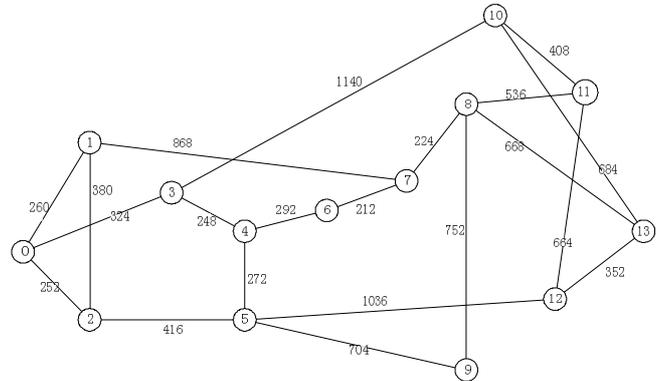


Fig.7. The test network topology for heuristic algorithm.

We first test the performance of blocking probability for SBPBG by comparing with the SBPP [28]. In Fig. 8, it is shown that with the number of arriving traffic demands becomes larger, the blocking probabilities for SBPBG and SBPP increase. The reason is that when the network load is larger, there will be no free resources for subsequent traffic demands, and thus more following traffic demands will be blocked. We can also see from the figure that blocking probability for SBPBG is better than that of the SBPP. This is caused by the guard band slots saving. The saving spectrum can provide service for more future traffic demands.

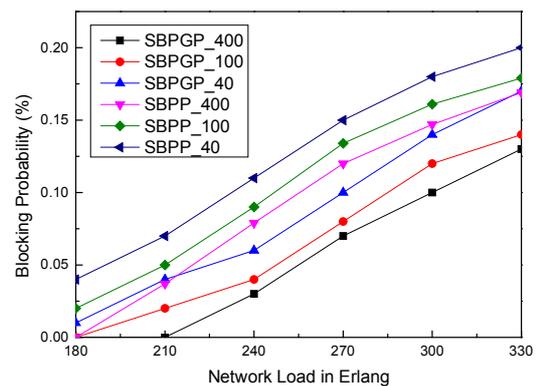


Fig.8. Comparison of blocking probability between SBPBG and SBPP with different network load.

In Fig. 9, we test the performance of total port-cost for SBPBG by comparing with the SBPP. We assume the network load is below 150 because there is no traffic demand blocked. We can see that the total port-cost for SBPBG is lower than that of SBPP. The reason for this is, due to less consumed transponder resources in SBPBG, the utilization ratio of existing lightpath is higher. That means more traffic demands

can be grouped together in SBPGP. Therefore, the number of new built lightpaths is decreasing and the total port-cost of SBPGP is smaller than that of SBPP.

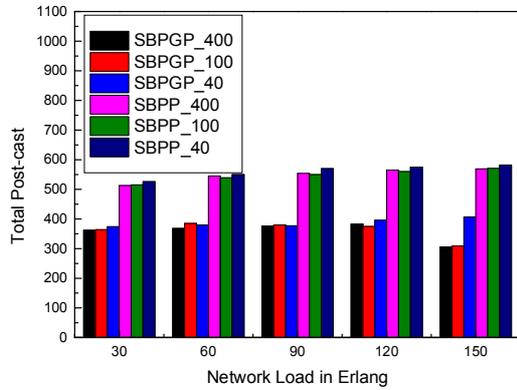


Fig.9. Comparison of total port-cost between SBPGP and SBPP with different network load.

In Fig. 10, it is shown that as the number of traffic demands increases, the spectrum utilization ratio increases. The reason is that the coming traffic demands need more spectrum resources to accommodate themselves. We can see that the spectrum utilization ratio for SBPGP is lower than that of SBPP. The reason is that the SBPGP considering the grooming technology which can save more spectrum resources. Therefore, the SBPGP can achieve the reduction of total spectrum and its spectrum utilization ratio will be lower.

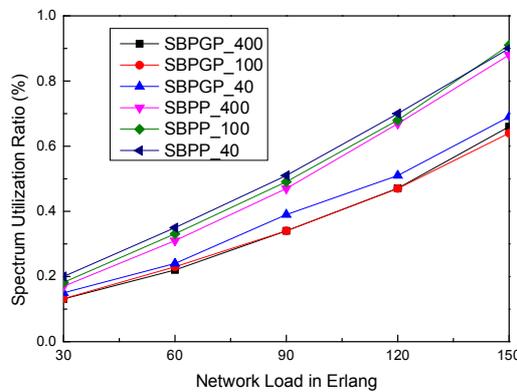


Fig.10. Comparison of spectrum utilization ratio between SBPGP and SBPP with different network load.

Fig. 11 shows the total power consumption for SBPGP by comparing with the SBPP under different network load. It is shown that with the number of arriving traffic demands becomes larger, the total power consumption for SBPGP and SBPP increases. But we observe that significant power savings are achieved by using grooming technology: e.g., nearly 100kW power saving improvement occurs when the network load is at 60Erlang. The reason is that, multiple traffic demands can share a single transponder, and the term of transponder resource sharing by using traffic grooming takes place completely on the optical layer, which reduces the number of

O-E-O conversion components at intermediate nodes, thus also potentially lowering the power consumption.

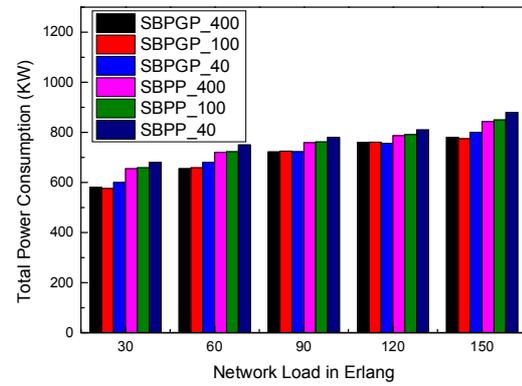


Fig.11. Comparison of total power consumption between SBPGP and SBPP with different network load

Fig. 12 shows the power savings caused by BVT under different network load, which is defined as the ratio of the saved power in kW by using grooming technology over the power consumption without grooming. It is shown that with the number of arriving traffic demands becomes larger, the power savings for different line rates increase slightly. The reason is that, when the network load is larger, a traffic demand can use the existing lightpaths rather than set up a new lightpath, which reduce the power consumption of BVT. We can also observe that the low line rate traffic has better performance on power savings than high line rate traffic. The reason is that, when line rate increases, a transponder can be filled with fewer traffic demands.

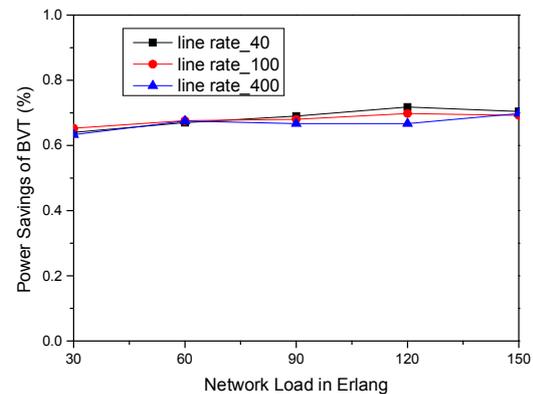


Fig.12. Comparison of power savings with different network load

## VII. CONCLUSION

This paper studied the survivability in software-defined elastic optical network. We considered the shared backup path protection with the grooming technology. We firstly introduced the problem and developed an ILP formulation for it. Then, we proposed a heuristic algorithm SBPGP to provide the protection for software-defined elastic optical network. In SBPGP scheme, we considered four grooming roles. For each

traffic demand, the working path and the backup path should be first considered to groom into existing lightpaths respectively. Thus, we can save more frequency resources and provide service for more following demands. Simulation results show that the proposed SBPGP scheme can achieve better performances than the traditional schemes. Especially, compared to SBPP without grooming, SBPGP is able to achieve significant power savings.

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