Spectrum-Maximized Sharing Protection in Software-Defined Elastic Optical Networks

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Abstract: We develop a spectrum-maximized sharing protection approach (SMSPA) to improve the spectrum efficiency in software-defined elastic optical networks. Simulation results show that SMSPA significantly reduces the blocking probability and spectrum occupation ratio.

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1. Introduction
In recent years, the software-defined elastic optical networks (SD-EONs) have attracted intensive attentions due to both the high spectrum efficiency and the flexible resource management. Additionally, in order to guarantee quality of service (QoS), the traffic demands need to provide the path protection based on the high service level assignment. Thus the optical network survivability should be considered when we establish the lightpaths of traffic demands, where we employ shared-path protection to guarantee QoS and to improve the spectrum efficiency in the SD-EONs. Many studies have investigated the problems of the SD-EONs and the network survivability, which is summarized as follows. The benefits of the SD-EON control plane to drive fast restoration were demonstrated by improving recovery time on flexible optical networks [1]. In a SD-EON, the data center service localization architecture was proposed to optimize the network resources based on virtual resources migration [2]. Demonstration of cooperative resource allocation was investigated by measuring the lightpath provisioning latency and blocking probability in the SD-EONs [3]. A multi-controller collaboration framework was also demonstrated via field demonstration of multi-domain software-defined transport networking with multi-controller collaboration [4]. However, the spectrum efficiency is not investigated by considering the shared protection in the SD-EONs. Thus this paper mainly focuses on the spectrum efficiency improving and blocking probability of traffic demands reducing in the SD-EONs.

2. Network model and problem statement
The architecture of a SD-EON is shown in Fig. 1 (a). Each node on optical layer denotes a switching node that corresponds to an array of bandwidth variable wavelength cross-connects (BV-WXCs), where BV-WXCs are implemented by using bandwidth variable wavelength selective switches (BV-WSSs). Each BV-WXC is controlled by an OpenFlow agent, which is referred as an extended OpenFlow-enabled BV-WXC (OF-BV-WXC). An OpenFlow controller named NOX [5] controls all BV-WXCs by an extended OpenFlow protocol, and manages all information of both fiber links and the spectrum resources by the centralized control on the whole EON. A SD-EON is defined as a directed network graph $G(V, E, F)$, where $V=\{v_1, v_2, v_3, \ldots, v_n\}$ denotes a set of switching nodes, $E=\{e_1, e_2, e_3, \ldots, e_m\}$ is a set of fiber links, and $F=\{f_1, f_2, f_3, \ldots, f_k\}$ is a set of available frequency slots. $|V|$, $|E|$, and $|F|$ represent the number of switching nodes, the number of fiber links, and the number of available frequency slots in a fiber link, respectively. Here, we define each traffic demand as follows:

$$R=R(s, d, BR)$$

where $s$, $d$, and $BR$ represent the source node, destination node, and the bandwidth requirement, respectively. Guard bands (GBs) are provisioned between traffic demands on the same fiber link in order to reduce interference between adjacent connections, which are assumed to have a width of GB frequency slots. We define the problem as follows:

We are given a directed network graph as a SD-EON, $G(V, E, F)$, a set of traffic demands, $Rs(s, d, BR)$, and a set of frequency slots $F=\{f_1, f_2, f_3, \ldots, f_k\}$ on each fiber link. We set several frequency slots as the guard bands. For each traffic demand, we must find the primary and backup paths to guarantee the network survivability. We must allocate the spectrum resources on the primary and backup paths in a SD-EON. Note that the allocated spectrum resources satisfy the spectrum continuity constraint along a path and the spectrum consecutiveness constraint in the frequency domain on a fiber link. Our objective is to improve the spectrum efficiency and to reduce the blocking probability for the shared-path protection in the SD-EONs. Therefore, two different shared-path protection approaches are developed to minimize the blocking probability and to improve the spectrum efficiency in the SD-EONs.

3. Spectrum-optimized sharing protection approaches
To reduce the blocking probability of traffic demands, we propose a spectrum-maximized sharing protection approach (SMSPA) to improve the spectrum efficiency in the SD-EONs. For each traffic demand, we need to
compute both primary path and link-disjoint backup path by running the $K$ shortest paths (K-SP) algorithm. We then select one path with the minimum number of hop counts as the primary path and allocate the working spectrum resources by first fit (FF). We also select a path with the spectrum-maximized sharing resources as the backup path from $K$ candidate backup paths, where these spectrum-maximized sharing resources by checking all frequency slots from lowest index to the highest index on $K$ candidate backup paths are used for the backup spectrum resources. We can describe the details of SMSPA as follows.

### Heuristic approach: SMSPA

**Input:** A network $G(V, E, D)$, a set of traffic demands $R_s(s, d, BR)$.

**Output:** Establish each $R(s, d, BR)$.

1. **Step 1:** For a $R(s, d, BR)$, the $K$ candidate primary paths are found by the $K$ shortest path (K-SP) algorithm, and they are stored into a primary path set $\varphi(x) = \{x_1, x_2, ..., x_K\}$ for these $K$ primary paths.

2. **Step 2:** The $i$th primary path with the minimum number of hop counts among the primary path vector $\varphi(x)$, i.e., $x_i \in \varphi(x)$ is selected as the using primary path. If no primary path can be found, drop this $R(s, d, BR)$, and run Step 1 again.

3. **Step 3:** Search for the available frequency slots based on the bandwidth requirement with BR frequency slots along the $x_i$ primary path by first fit approach, allocate these spectrum resources on the $x_i$ primary path for this traffic demand $R(s, d, BR)$. If no available frequency slots are successfully allocated, drop this $R(s, d, BR)$ and run Step 1 again.

4. **Step 4:** Delete all links $(k, l)$ on the $x_i$ primary path, run the K-SP algorithm again to obtain $K$ link-disjoint backup paths, and put them into a backup path set $\Omega(y) = \{y_1, y_2, ..., y_K\}$ for these $K$ backup paths. If no backup path is found, i.e., $\Omega(y) = \emptyset$, where the notation $\emptyset$ denotes the empty set, drop this $R(s, d, BR)$, and run Step 1 again.

5. **Step 5:** Search for the available frequency slots based on the bandwidth requirement with BR frequency slots, select a backup path $y_j \in \Omega(y)$ with the spectrum-maximized sharing resources as the using backup path, and allocate these available frequency slots along this backup path $y_j$. If no available frequency slots are successfully allocated on $\Omega(y)$, drop this $R(s, d, BR)$, or else establish this $R(s, d, BR)$.

For comparison, we also introduce a traditional spectrum sharing protection approach (TSSPA) to reduce the blocking probability of traffic demands in the SD-EONs. For each traffic demand in TSSPA, the primary path and link-disjoint backup path are calculated by the K-SP algorithm and one path with the minimum number of hop counts is selected as the using primary path or backup path. We then employ the first fit approach to search the available spectrum resources on the selected primary path and backup path, and allocate these available frequency slots to the working and backup spectrum resources. The steps of TSSPA are similar to those of SMSPA, but the backup path selection is a path with minimum hop counts in Step 4 of SMSPA and spectrum resources are allocated by first fit in Step 5 of SMSPA.

![Fig. 1](image-url). An architecture of a software-defined elastic optical network (a), and the status of spectrum occupying for SMSPA (b) and TSSPA (c).
5,000 traffic demands are generated for each data point in an experiment. The bandwidth requirements for each traffic arrival follow a Poisson process and the traffic holding time follows a negative exponential distribution. EONs, where each fiber link is bidirectional and each node denotes an array of the programmable BV-WXCs. The frequency slots is considered. There are 150 available frequency slots for each fiber link and each frequency slot has the 12.5 GHz spectrum widths. Both primary path and backup path are computed by the K-SP algorithm with K=3.

In Fig. 2 (a), compared to TSSPA, SMSPA reduces by 6.5% and 8.7% blocking probability under GB=2 and GB=1, which verifies that SMSPA always outperforms the blocking probability than TSSPA. The reason is that SMSPA employs the method of finding the spectrum-maximized sharing resources as backup spectrum resources on the backup path, which results in SMSPA consuming fewer free frequency slots among backup path than TSSPA, and results in many free spectrum resources being saved. Additionally, the spectrum utilization ratio of SMSPA is lower than that of TSSPA, which greatly increases with the traffic load rising. Only 2.3% and 2.2% spectrum utilization ratio is save by SMSPA under GB=2 and GB=1 compared to TSSPA. The main reason is that the fewer free spectrum resources on backup path are consumed by SMSPA when the spectrum-maximized sharing approach is used for finding the backup spectrum resources. From another view, SMSPA reduces about 2.6% and 2.8% number of frequency slots/Erlang compared to TSSPA under GB=2 and GB=1. Also, the number of frequency slots/Erlang slowly reduces with traffic load increasing, since much more backup spectrum resources are shared if there are more traffic demands staying on a SD-EON.

5. Simulation and results

We adopt the NSFNET topology [6] to evaluate the network performance between SMSPA and TSSPA in the SD-EONs, where each fiber link is bidirectional and each node denotes an array of the programmable BV-WXCs. The traffic arrival follows a Poisson process and the traffic holding time follows a negative exponential distribution. 50000 traffic demands are generated for each data point in an experiment. The bandwidth requirements for each traffic demand are uniformly distributed within [2, 5] frequency slots and a guard band with GB=1 or GB=2 frequency slots is considered. There are 150 available frequency slots for each fiber link and each frequency slot has the 12.5 GHz spectrum widths. Both primary path and backup path are computed by the K-SP algorithm with K=3.

6. Conclusions

In this paper, SMSPA and TSSPA are developed to optimize the spectrum efficiency in the SD-EONs. Simulation results show that the spectrum-maximized sharing protection approach significantly improves spectrum efficiency and greatly reduces the blocking probability compared to the traditional spectrum sharing protection approach.

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