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Shared protection based virtual network mapping in space division multiplexing optical networks

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ABSTRACT

Space Division Multiplexing (SDM) has been introduced to improve the capacity of optical networks. In SDM optical networks, there are multiple cores/modes in each fiber link, and spectrum resources are multiplexed in both frequency and core/modes dimensions. Enabled by network virtualization technology, one SDM optical network substrate can be shared by several virtual networks operators. Similar with point-to-point connection services, virtual networks (VN) also need certain survivability to guard against network failures. Based on customers' heterogeneous requirements on the survivability of their virtual networks, this paper studies the shared protection based VN mapping problem and proposes a Minimum Free Frequency Slots (MFFS) mapping algorithm to improve spectrum efficiency. Simulation results show that the proposed algorithm can optimize SDM optical networks significantly in terms of blocking probability and spectrum utilization.

1. Introduction

As Internet traffic continues increasing, the capacity of Single-Core Fiber (SCF) or Single-Core Fiber (SMF) is being challenged [1]. To improve channel capacities of fibers, Space Division Multiplexing (SDM) has been introduced to optical networks to explore potential spectrum resources in spatial dimension, and Multi-Mode Fiber (MMF) and Multi-Core Fiber (MCF) are two popular kinds of infrastructure for supporting space division. In SDM optical networks, spectrum resource is multiplexed not only in frequency dimension, but also in mode/core dimension. Besides Routing, Spectrum/Wavelength Assignment (RSA/RWA), mode/core has to be selected for service provisioning in SDM optical networks [2].

Enabled by network virtualization technology, Virtual network (VN) is emerging as a new type of service to provide topology-level connections. To provision a given VN request, which is composed of several virtual nodes and virtual links, network infrastructure operators need to map required virtual entities to physical substrates and allocate required resources for them. Above procedures are usually concluded as VN mapping, and several works have studied VN mapping problem in the context of Wavelength Division Multiplexing (WDM) optical networks and Elastic Optical Networks (EON) [3–5]. VN mapping in SDM optical networks is different from that in WDM optical networks or EON, because spatial dimension of SDM has significant impact on spectrum resource provisioning. Ref. [6] studied crosstalk's impact on VN mapping in SDM optical networks, and proposed crosstalk-aware mapping algorithms to reduce the blocking caused by crosstalk. Ref. [7] have discussed the feature of Mode-Dependent Loss (MDL) in SDM optical networks, and the impact of MDL on VN provisioning is studied based on an analytical model of MDL.

Survivability of VN is an important topic in optical networks [8], and it aims to improve VN's fault tolerance in case of physical infrastructure failures. Protection is a popular approach to provide survivability to VNs by providing extra backup resources. Focusing on the problem of protection resource provisioning, Ref. [9] has discussed several protection schemes from the perspectives of network operators and customers. From network operators' perspective, two kinds of protection can be provided for a VN, and they are topology level protection and connection level protection. For topology level protection, Ref. [9] reported a scheme to provide dedicated backup resource for each link of a VN. In practice, not all VN customers need dedicated protection for their VNs; instead, they may have different Service Layer Agreement (SLA) requirements for their VNs; for example, some customers may need 1 + 1 dedicated backup connection, but some others may need 1: N shared backup connections. Different protection policies provide different level survivability, but need different amounts of spectrum resources from network infrastructures. In the scenario, where multiple VNs have heterogeneous survivability requirements, VN mapping algorithms may have strong impacts on infrastructure's efficiency. However, the mapping problem in such scenario have not been studied yet, according to the best of our knowledge. This work focuses on the shared protection based VN mapping problem in SDM optical

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networks, and tries map VN requests with heterogeneous survivability requirements in a spectrum-efficient way.

In this paper, we set up a resource model for MMF-based SDM optical networks to measure spectrum resource in both link and mode dimensions. Based on the resource model, we propose a Minimum Free Frequency Slots (MFFS) mapping algorithm to optimize spectrum utilization for VN provisioning, while meeting heterogeneous protection policies required by each VN. The proposed algorithm is evaluated via software simulations, and results show it can optimize resource utilization of SDM optical network significantly in terms of VN blocking probability and shared ratio of spectrum resources.

2. Related works

This section reviews the existing survivability related works in optical networks from two perspectives: survivability in none-SDM optical networks; survivability in SDM optical networks.

Regarding the survivability issues in none-SDM optical networks, shared backup-path is a famous approach for improving resource efficiency. To provision shared backup-path protection efficiently, Ref. [10] developed integer linear programming (ILP) models to minimize both the required spare capacity and the maximum number of link frequency slots (FSs) used. In an extended scenario, which is IP over EON, Ref. [11] studied the traffic grooming problem based on shared backup-path protection, and developed heuristic algorithms to enable joint spare capacity sharing in both IP and optical layer. In reality, when considering provisioning backup lightpath in EONs, one fact that should be kept in mind is that the distance of working and backup lightpaths are usually not same, thus, modulation format is another issue that matters when studying protection schemes in EONs. Fortunately, Ref. [12] noted this case and developed a distance adaptive RSA approach based on the concept of spectrum window planes (SWPs) to maximize protection spectrum sharing. In addition to lightpath provisioning itself, spectrum fragmentation is another issue that related with shared backup-path protection. To improve spectrum efficiency while considering spectrum fragmentation, Ref. [13] proposed two protection-path spectrum defragmentation algorithms to re-establish protection lightpaths. As Ref. [9] discussed, network operators can provide topology level protection for a virtual network. Therefore, to provide survivability for a VN, Ref. [14] formulated an Integer Linear Program (ILP) model to map VNs over EON substrate efficiently and it provides different survivability schemes against any single physical link failure. To minimize the resource consumption of both working and backup paths of VNs, Ref. [15] designed a different dynamic cost model (DDCM) for each sharable frequency slot (FS) and proposed a shared protection VON mapping (SPVM) algorithm based on DDCM. Beyond resource efficiency, VN's availability is another issue for VN mapping, as it is supported by assigned protection resource. To provide a certain availability for a VN request, Ref. [16] developed a matrix-based approach for calculating the availability of a VON mapping with shared backup path protection.

In SDM optical networks, survivability should be reconsidered as the space dimension needs to be handled when provisioning end-to-end connections and VNs. Targeting on static shared backup-path provisioning problem in MCF networks, Ref. [17] formulated an integer linear programming (ILP) model for working/backup path computation considering inter-core crosstalk and its MIMO-based crosstalk suppression. As to dynamic backup-path provisioning in SDM optical networks, Ref. [18,19] proposed a shared backup-path protection algorithm for MFC based networks to use the backup paths that are interleaved with primary paths in order to generate less crosstalk per slot. Refs. [6,7] studied the VN mapping issues in SDM optical networks, but survivability is not mentioned. Thus, to the best of our knowledge, studies of VN survivability in SDM optical networks have not been reported yet. This work will study shared protection based VN mapping problem while considering heterogeneous survivability requirements of different VNs.

3. Resource model for MMF-based SDM optical networks

A given MMF-based SDM optical network is denoted by a graph $G_p(N_p,L_p,M,S)$, where N_p is a set of physical nodes, L_p. is a set of physical links, M is a set of modes in each physical link, and S is a set of Frequency Slots (FSs) in each mode. Spectrum resource in MMF-based SDM networks is distributed in link, mode, and frequency dimensions. To present such three dimensional resource more accurately, we define a Mode-Spectrum (MS) matrix $O_{i,j}$ to describe the occupation status of each FS in each mode in a fiber link *i-j*. In this matrix, $u_{m,n}^{i,j}$ is a binary key for the m_{th} FS in n_{th} mode. For $u_{m,n}^{i,j}$, false means the FS it refers to is occupied, and true means the FS it refers to is free. The excitation and separation of individual modes in a MMF can be realized by the Mode Selective couplers (MSC) [20]. The MSC is comprised of a MMF arm and a SMF arm, coupling the LP01 mode of the SMF to a specific higher-order mode of the MMF.

$$O_{i,j} = \begin{bmatrix} u_{1,1}^{i,j} & u_{1,2}^{i,j} & \cdots & u_{1,M}^{i,j} \\ u_{2,1}^{i,j} & u_{2,2}^{i,j} & \cdots & u_{2,M}^{i,j} \\ \vdots & \vdots & \ddots & \vdots \\ u_{F,1}^{i,j} & u_{F,2}^{i,j} & \cdots & u_{F,M}^{i,j} \end{bmatrix}_{M*F}$$

VN requests represent network customers' requirement on VN topology and capacity in each virtual link, and a VN request can be denoted by a graph $G_v(V_v,E_v)$, where V_v is a set of virtual nodes, and E_v is a set of virtual links. For each virtual link $l_v \in E_v$, it is associated with two parameters; 1) C_{l_v}, bandwidth capacity of l_v, 2) n_{l_v}. VNs' demand on survivability level. To be more specific, n_{l_v} is a threshold number of peers for sharing the protection connection for link l_v. More peers for sharing one backup connection means higher competition with peers when physical failures occur. For example, $n_{l_v} = 1$ means link l_v requires a dedicated backup connection, while $n_{l_v} = 3$ means that link l_v can share its backup connection with two other virtual links. Fig. 1 shows an overview of VNs with shared backup connections. It is notable that VN-1 and VN-2 are mapped to the same substrate. Besides working connection for each virtual link, a backup connection also needs to be provided for each virtual link. Take virtual link 2-1-5 in VN-1 and VN-2 as examples, their working connections are mapped to 2-5 and 2-4-5, respectively. Assuming that both VN-1 and VN-2 do not require a dedicated backup connection, virtual link 2-5 in VN-1 and VN-2 can share one common physical link 2-1-5 in the substrate as their backup connections.

Since VNs in optical networks are usually operated by enterprise customers for connecting distributed datacenters, the provisioning of VN nodes is not fully flexible; instead, VN nodes should be mapped to the physical nodes, where customers' datacenters are located. Based on this consideration, the mapping relationship between virtual and

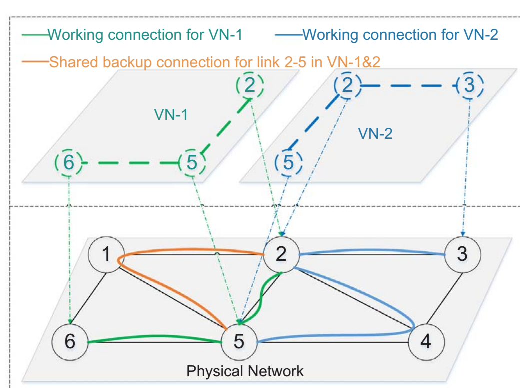

Fig. 1. Overview of VNs with shared backup connection.