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Super-channel oriented routing, spectrum and core assignment under crosstalk limit in spatial division multiplexing elastic optical networks

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ABSTRACT

With the capacity increasing in optical networks enabled by spatial division multiplexing (SDM) technology, spatial division multiplexing elastic optical networks (SDM-EONs) attract much attention from both academic and industry. Super-channel is an important type of service provisioning in SDM-EONs. This paper focuses on the issue of super-channel construction in SDM-EONs. Mixed super-channel oriented routing, spectrum and core assignment (MS-RSCA) algorithm is proposed in SDM-EONs considering inter-core crosstalk. Simulation results show that MS-RSCA can improve spectrum resource utilization and reduce blocking probability significantly compared with the baseline RSCA algorithms.

1. Introduction

With the fast development of various applications, such as cloud computing and video on demand (VoD), the demand for network bandwidth has been increasing significantly during the past decade. As an effective approach to support high-speed optical channels beyond 100 Gbit/s, elastic optical network (EON) is proposed to improve the spectrum efficiency of optical networks [1]. Sliceable transponder and elastic regenerator can promote the development of EON [2], and software defined networking control technology can manage the spectrum resource efficiently [3,4]. Nevertheless, the transmission capacity of single-core fiber (SCF) in EONs will reach the physical limitation soon [5]. To meet the increasing demands for network bandwidth, spatial division multiplexing (SDM) is introduced as a novel transmission technology, which can improve the capacity of single fiber link by using multi-core fiber (MCF) or multi-mode fiber (MMF) [6,7]. Supported by MCF, spatial division multiplexing elastic optical networks (SDM-EONs) will become an important form of future optical transport networks.

This paper mainly focuses on SDM-EONs based on MCF because it is more practical compared with MMF. On the one hand, spectrum continuity constraint has been alleviated, which means that the signal can interchange between different cores freely while maintaining the common spectrum slice [8]. On the other hand, inter-core crosstalk may occur when same spectrum slices in neighbor cores are activated simultaneously. Some methods have been proposed for measuring the inter-core crosstalk in MCF [9]. At networking level, some algorithms are proposed to avoid inter-core crosstalk in routing, spectrum and core assignment (RSCA) process, such as a first-fit scheme and ILP-based scheme [10]. First-fit scheme is generally used to ensure both slot contiguity and continuity constraints along the path. Based on first-fit scheme, ILP-based scheme is proposed to minimize the maximum number of spectrum slices. However, the proposed first-fit and ILP-based schemes do not consider the dynamic traffic, and would result in high blocking probability and spectrum fragments. Taking fragmentation into account, a pre-defined core classification scheme is proposed to reduce the fragmentation [5]. In general, all the works above take inter-core crosstalk into account and aim to provide light paths under the spectrum contiguity and continuity constraint of sub-carriers in SDM-EONs. Then the concept of super-channels is introduced into SDM-EONs, which bring some improvement about RSCA schemes. Ref. [11] considers three types of super-channels, including spatial, spectral and spatial-spectral mixed super-channels, and presents some resource allocation policies to provide spectrum or spatial super-channels. However, few works focus on the provisioning of mixed super-channels in SDM-EONs, which will be of great value for industry. Furthermore, inter-core crosstalk is negligible in aforementioned policies. Based on that, this paper proposes a mixed super-channel oriented rout-

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ing, spectrum and core assignment (MS-RSCA) scheme in SDM-EONs. It can not only provide mixed super-channels to carry service requests in spatial and spectral dimension simultaneously, but also consider inter-core crosstalk.

2. Network model

In this paper, we consider the problem of RSCA in SDM-EONs, where the spectrum resource can be simplified as Frequency Slots (FSs) which represent quantized units in each MCF. We formulate the physical network as a graph $G(V, E)$, where V is a set of nodes, and E is a set of MCF links. In the networks, each link $L (L \in E)$ is composed of a core set C, and each core has a set of FSs. To express the network resource status more clearly, matrix A_l is defined to denote the FS status of link l.

$$A_l = \begin{bmatrix} O_{1,1} & O_{1,2} & \dots & O_{1,c} \\ O_{2,1} & O_{2,2} & \dots & O_{2,c} \\ \dots & \dots & \dots & \dots \\ O_{f,1} & O_{f,2} & \dots & O_{f,c} \end{bmatrix} \tag{1}$$

As shown in formulation (1), A_l is composed of c columns and f rows, which represents c cores in link l and f FSs in each core. The matrix element $O_{i,j}$ is a binary value, which is used to denote the occupation status of FS i in core j. For example, $O_{i,j} = 1$ means FS i in core j is available, while $O_{i,j} = 0$ means it is occupied. For a pending connection request, we formulate it as $R(s, d, b)$, where s and d are the source and destination nodes, and b is the required bitrates of this request. Once a request arrives, the operator needs to select modulation format such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) [12] according to signal-to-noise ratio (SNR) in the selected path.

In SDM-EONs, inter-core crosstalk is a key physical constraint, which will severely impact the transmission signal quality. The inter-core crosstalk may occur when the common frequency spectrums in adjacent cores are used simultaneously. To decrease the crosstalk and achieve dense core arrangement, a trench-assisted MCF (TA-MCF) is developed [13]. In this paper, a seven-core fiber, which has relatively low crosstalk due to reduced macro-bending loss and micro-bending loss, is used as an example. This seven-core model is composed of two types of cores, including a center core which has six adjacent cores and six marginal cores which may be reflected by other three adjacent cores. The schematic diagram of the seven-core model is shown in Fig. 1(a). Fig.1(b) shows an index profile of a core element, where r_1 means half of d in Fig.1 (a), and $r_3 - r_2$ is the trench in Fig.1(a). To estimate the statistically mean inter-core crosstalk of a MCF, we utilize the model in [14] which is supported by the coupled-mode theory and measures the inter-core crosstalk with fiber parameters. For weakly-coupled MCF with core arranged in a hexagonal array, the formula (2) and (3) can be formed as follows, where XT is the mean inter-core crosstalk [15].

$$h = \frac{2k^2 r}{\beta w_{tr}} \tag{2}$$

$$XT = \frac{n - n \cdot exp[-(n+1) \cdot 2hL]}{1 + n \cdot exp[-(n+1) \cdot 2hL]} \tag{3}$$

In formulation (2), h denotes the mean increase in inter-core crosstalk per unit length. k, r, β, and w_{tr} are the relevant fiber parameters, representing the coupling coefficient, bend radius, propagation constant, and core-pitch. For a particular fiber, h is a constant value which can be calculated with the constant parameters in Ref. [16]. Formulation (3) is a ratio of power (in a specific core) originating from the rest of cores to the power that emanates from this specific core. In formulation (3), n is the number of the adjacent cores and L represents the fiber length. For the centered core which is depicted as C_7, n equals to six at maximum, while for other marginal cores, n equals to three. From the inter-core crosstalk calculation formulations, we note that the inter-core crosstalk is affected by the number of adjacent cores and the length of the fiber.

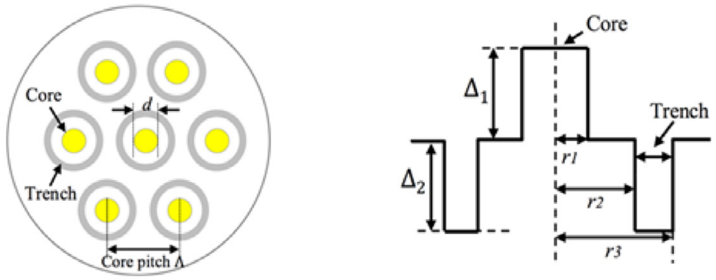
With the inter-core crosstalk constraint and the introduction of spatial dimension, spectrum allocation algorithms are extended to construct super-channels, such as spectral, spatial and mixed super-channels described as follows:

(1) Spectral super-channel: a set of contiguous single-carriers (sub-carrier), modulated with the same format are used to form a spectral super-channel and serve a given bit rate. It is continuous in spectrum dimension. This entails that each spectrum super-channel must share the same core (i.e., position in the spatial domain). A typical use of this super-channel is depicted as Service1 in Fig. 2.

(2) Spatial super-channel: by placing individual sub-channel at the same frequency on different cores. Groups of same-wavelength sub-channels are transmitted on separate spatial cores but routed together, which means that all signals must share the same spectral dimension (observe that no contiguity constraint is assumed). Spatial super-channel is constructed like Service 2 shown in Fig.2.

(3) Mixed super-channel: multiple spatial super-channel is extended at the Nyquist condition creating a spectral super-channel. Mixed super-channel is used as Service 3 shown in Fig.2.

Actually, there are some disadvantages for super-channel construction, especially for mixed super-channel. Firstly, the transport nodes should be able to split client data into multiple flows and send them to different sliceable transmitters. Secondly, the differ-



(a) Schematic of trench-assisted seven-core fiber; (b) schematic of a core with index trench

Fig. 1. Illustration of MCF.