Self-homodyne Spatial Super-Channel Based Spectrum and Core Assignment in Spatial Division Multiplexing Optical Networks

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Abstract. Space Division Multiplexing (SDM) has been introduced as a promising technique to improve the capacity of optical transport networks. In SDM optical networks, Multi-Core Fiber (MCF) is taken as the infrastructure, and the spectrum resources of one MCF are distributed in multiple cores. According to such features, self-homodyne spatial super-channel has been introduced to support setting up super-channels across multiple cores in one MCF, and it relaxes the contiguous constraint in traditional Elastic Optical Networks (EON). Based on self-homodyne spatial super-channel, this paper focuses on the problem of Spectrum and Core Assignment (SCA) in SDM networks. We set up a self-homodyne spatial super-channel based resource model, including several types of MCF with certain inter-core crosstalk. Accordingly, we proposed a Self-homodyne Spatial Super-channel based Spectrum and Core Assignment scheme. Simulation results show that the proposed scheme can improve the spectrum consumption ratio and reduce blocking probability significantly.

Keywords: Spatial Division Multiplexing · Spatial super-channel · Spectrum and Core Assignment

1 Introduction

With the development of flexible and dynamic network based applications (e.g., cloud computing, video on demand and time varying services), the demand for network bandwidth has been increasing significantly during the past several years, and this trend will continue. As an effective approach, which can support high-speed optical channels beyond 100 GB/s, Elastic Optical Networks (EON) has been proposed to improve the spectrum efficiency of current optical networks. Nevertheless, the transmission capacity of Single-Core Fiber (SCF) will reach the physical limitation soon [1]. To meet the increasing demands for network bandwidth, Spatial Division Multiplexing (SDM) has been investigated as an infrastructural technique, which can improve the capacity of single fiber link up to 1 Pbps, by using Multi-Core Fiber (MCF) [2] or Multi-Mode Fiber

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(MMF). Then, spatial division multiplexing enabled elastic optical networks (SDM-EONs) will become the most important form of future optical transport networks.

MCF is mainly considered in the paper because it is more practical compared with MMF, which also brings some new features and challenges for optical networks. On the one hand, spectrum continuous constraint has been alleviated, which means that the signal can interchange between different cores freely while maintaining the same spectrum slice On the other hand, inter-core crosstalk may occur when the same spectrum slice overlaps in neighbor cores. Some methods has been proposed for measuring the crosstalk statistically in MCF. At networking level, some schemes were proposed to avoid inter-core crosstalk in Routing, Spectrum and Core Assignment (RSCA) process, such as a first-fit scheme and ILP-based scheme [3]. First-fit scheme is generally used to ensuring both slot consistency and continuity constraints along the path. Based on first-fit, ILP-based scheme was proposed to minimize the maximum number of spectrum slices required on any core of MCF. However, the proposed first-fit and ILP schemes do not consider the dynamic traffic and would result in higher blocking probability and spectrum fragments. Taking fragmentation into account, a pre-defined core classification scheme [4] was proposed to reduce the fragmentation of each core. In general, all the works above take cross-talk into account and aim to provision light-paths under the consistent and contiguous constraint of subcarriers in EON. Meanwhile, spatial super channel has been investigated from hardware perspective to relax the traditional contiguous constraint in spectrum dimension. By exploiting the highly correlated properties of different cores in one single MCF, Puttnam et al. show that spatial super channel and Self-Homodyne Detection (SHD) are available in MCF [5, 6]. To support self-homodyne spatial super-channel switching in SDM networks, a hybrid add-drop node that can realize low Optical Signal Noise Ratio (OSNR) is presented in [7]. However, all the above RSCA schemes, which are limited by traditional contiguous constraint, have not considered the self-homodyne spatial super-channel, especially under crosstalk-aware condition, thus they cannot achieve optimal resource efficiency in self-homodyne spatial super-channel enabled SDM networks. This paper focuses on the Spectrum and Core Assignment (SCA) problem in self-homodyne spatial super-channel enabled SDM networks.

This paper discusses the SCA problem based on self-homodyne spatial super channel. We set up a resource model for SDM optical networks to address the relationship between fiber, core and wavelength. According to the resource model, we also propose a self-homodyne spatial super-channel based spectrum and core assignment (SSS-SCA) scheme under the limitation of inter-core cross-talk (XT). Simulation results show that the proposed SCA scheme can reduce the blocking probability and improve the efficiency of resource network significantly.

2 Self-homodyne Spatial Super-Channel Based Resource Model and Crosstalk Analysis

In this paper, we consider the problem of SCA in the scenario of SDM enabled EONs, where the spectrum resource can be simplified as Frequency Slot (FS) in each MCF. We formulate the physical network as a graph $G(V, E)$, where V is a set of network nodes, and E is a set of MCF links. In SDM networks, each link $L(L \in E)$ is composed of a core set C, and each core has a set of FSs. In order to express the network resource occupation status more clearly, a matrix A_l is defined to denote the FS occupation status of fiber link l as (1).

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

As is shown above, 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 slot i in core j. For example, $O_{i,j}$ = 1 means the corresponding FS is available, while $O_{i,j}$ = 0 means occupied. For a pending end-to-end connection request, we formulate it as $R(s, d, b)$, where s and d are the source-destination node pair, and b is the required bitrates of this request. Once a request arrives, the network operator needs to select spectral modulation format [8] according to the Signal-to-Noise Ratio (SNR) in the selected path.

Trench-assisted MCFs [9] are the mostly preferred in SDM transmission due to crosstalk interference. This paper focuses the SCA problem under inter-core XT in 3 types of MCFs, including 7, 12, 19 core fibers as shown in Fig. 1.

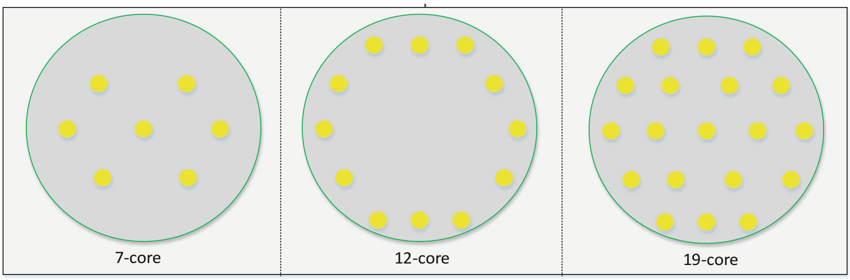

Fig. 1. MCFs with 7-core, 12-core, 19-core

In addition, inter-core crosstalk is a key constraint in SDM optical networks, and it would occur when the same frequency slot in adjacent cores is used simultaneously. Equations (2) and (3) is defined to evaluate the mean crosstalk XT for MCF [10].

$$h = (2 \cdot k^2 \cdot r)/(\beta \cdot wth). \tag{2}$$

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

In Eq. (2), h denotes the mean increase in crosstalk per unit length. k, r, β, and wth are the relevant fiber parameters, representing the coupling coefficient, bend radius, propagation constant, and core-pitch, respectively. In Eq. (3), n is the number of the adjacent cores and L represents the fiber length. For the centered core of 7-core MCF in Fig. 1, n equals to six, while for other marginal cores, n equals to three, which determinate the inter-core crosstalk policy to some extent. From the crosstalk calculation equations, we note that the crosstalk is affected by the number of adjacent cores and the length of the fiber.

3 Self-homodyne Spatial Super-Channel Based Spectrum and Core Assignment Scheme

In spatial super channel, high bitrates data streams are transported as groups of sub-channels occupying the same wavelength in separate cores. To simplify, in this case we assume that the optical nodes have the wavelength conversion ability, so that the spatial super channel can be constructed with different wavelengths in separated cores. This paper discusses the problem of SCA in spatial super channel enabled SDM networks. Traditionally, continuity is one of the most important constraints for building super channels in EONs, and many discontinuous FSs cannot be used to carry high bitrates requests. Taking Fig. 2(a) as an example, most FSs are unavailable which is due to higher inter-core crosstalk in the resource map except several free spectrum fragments. When a new service request arrives with the requirement of 5 FSs, no core has enough vacant continuous frequency slots and this request will be blocked. To handle this kind of un-optimal condition, we propose a Self-homodyne Spatial Super-channel based Spectrum and Core Assignment (SSS-SCA) scheme to build super channels on both core and spectrum dimensions. The idea of SSS-SCA can be illustrated as Fig. 2(b), where the FS groups of $\{O_{1,6}, O_{2,7}, O_{2,8}, O_{1,9}, O_{1,10}\}$ and $\{O_{3,1}, O_{3,2}, O_{4,3}, O_{3,4}\}$ in spatial dimension are selected to construct the spatial super channels for Service 1 and Service 2 respectively. SSS-SCA scheme still follows spectrum continuity constraint in frequency slot dimension, though distributed in different core dimensions.

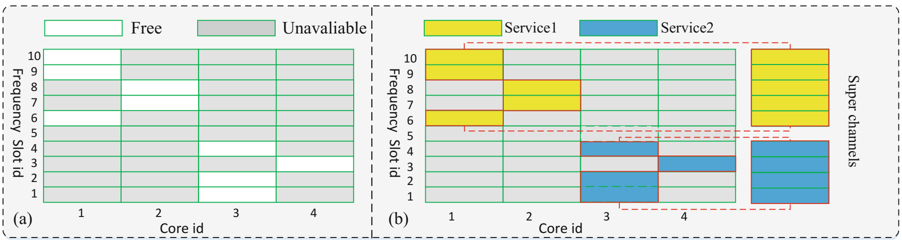

Fig. 2. (a) Common network occupation status one single link before using spatial super channel; (b) SCA with spatial super channels

The SSS-SCA scheme is described as follows.

Self-homodyne Spatial Super-channel based Spectrum and Core Assignment Scheme

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1: for a pending service request $R(s, d, b)$;
2: calculate routing path with KSP algorithm and get k shortest paths as a set $\{P\}$;
3: **if** there is no candidate path in $\{P\}$, **then**
4:    block this request $R(s, d, b)$;
5: **else**
6:    **for** each path $p_0 \in \{P\}$, **do**
7:       decide the appropriate modulation format, get crosstalk threshold XT_{TH} and calculate the number of required FS n;
8:       **for** each core c on path p_0, **do**
9:          calculate all the available FS segments as a set $\{F\}_{c,}$
10:          **if** there exists a FS segment whose length $m \geqslant n$, **then**
11:             calculate the crosstalk XT;
12:             **if** $XT \leqslant XT_{TH}$, **then**
13:                allocate the required FS;
14:             **else if** $m<n$ or $XT \geqslant XT_{TH}$, **then**
13:                iterate over all core dimensions to construct spatial superchannel with available FSs, get $\{M\}$;
16:                **if** there is a candidate m_k in $\{M\}$ whose length $l \geqslant n$ in $\{M\}$ which satisfies $XT \leqslant XT_{TH}$, **then**
17:                   allocate the required FS;
18:                **else**
19:                   block the service request;
20:                **end if;**
21:             **end if;**
22:          **end if**
23:       **end for**
24:    **end for**
25: **end if**

The SSS-SCA algorithm above provides the overall procedure for achieving dynamic service provisioning. Lines 1–4 are for calculating an optimal path candidate p_O, using KSP algorithm. Line 5–25 show the details of allocating FSs. Specifically, we first calculate the unoccupied FSs of the whole p_O according to the consistency constraint, and get all the available FSs segments as a set $\{F\}_c$ for each core c on this path. From all the available FS segments of path p_O, find a FSs segment f which contains more than n continuous slots, and allocate the required FSs from it directly. If no available FSs segment, a spatial super-channel should be constructed as following procedures. Integrating all the FS segment of path p_O to construct a new spatial super-channel segment group $\{M\}$ where each element $m \in \{M\}$ is selected as the policy of being continuous in spectral dimension (whether continuous in spatial dimension or not). If there is an appropriate m_k which can afford more than n slots for which the inter-core crosstalk is below XT_{TH}, then the required FSs are allocated. Else, block the service request.

4 Performance Evaluation

We evaluate the performance of the proposed SCA scheme through simulations on NSFNET topology with14 nodes and 21 links, where each node is configured as optical nodes with the ability of wavelength conversion, and each link is configured as MCF. The number of frequency slots per core is set to 300. Under each traffic load, the simulator generates 5000 end-to-end requests following Poisson model with the fixed departing rate 0.04. The source and destination n nodes of each request are generated randomly. In this simulation, the bitrate request is simplified as the number of FSs by assuming that the modulation format is fixed as BPSK. Taking the Random SCA scheme as the benchmark, we evaluate the performance of SSS-SCA in terms of blocking probability and Resource Consumption Ratio in two conditions. (1) The traffic load is fixed to 2000 Erlang, and the number of required FSs of each request is generated randomly between 10 and 15. We evaluate the performance of the proposed scheme under 3 types of MCFs in this condition. (2) The core number of each MCF link is fixed to be 7, and the number of required FSs are evenly distributed in following two intervals: from 5 to 10 and from 10 to 15. We evaluate the performance of SSS-SCA under different traffic loads.

The figures shown above indicate that the blocking probability of SSS-SCA scheme is lower than that of random SCA scheme, while the Resource Consumption Ratio of SSS-SCA scheme is higher than that of random-SCA scheme both in experimental MCFs and traffic load. Both advantages are due to the characteristics of SSS-SCA scheme of utilizing distributed FSs to configure spatial super channel. Therefore, less spectrum fragments will result in higher Resource Consumption Ratio and lower blocking probability eventually.

Figures 3 and 4 compare the performances of random SCA scheme and SSS-SCA scheme in multi-core MCFs, and it is notable that SSS-SCA performs better in the conditions of 7-core, 12-core and 19-core MCF.

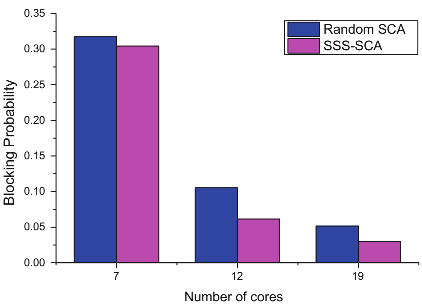

Fig. 3. Blocking probability of various core number (Erlang = 2000).

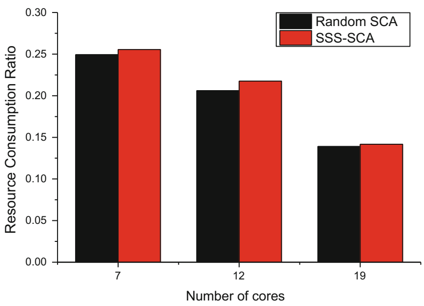

Fig. 4. Resource consumption ratio of various core number (Erlang = 2000).

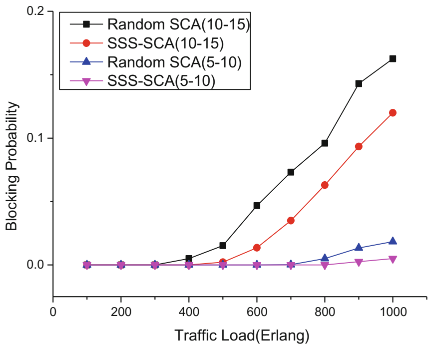

Fig. 5. Blocking probability of various traffic load (Core = 7).

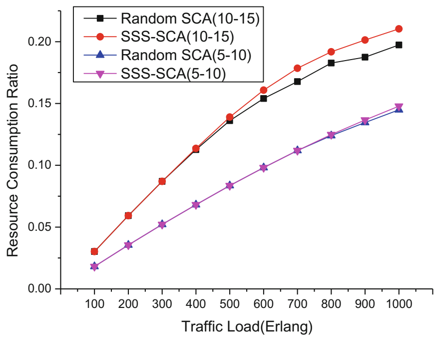

Fig. 6. Resource consumption ratio of various traffic load (Core = 7).

Figures 5 and 6 show that both blocking probability and spectrum Resource Consumption Ratio grow constantly as the traffic load increasing from 100 to 1000 Erlang. In the comparison between the two conditions where the required FSs are distributed in different ranges, it is notable that the advantages of the proposed SSS-SCA scheme are more significant in the condition with more FS requirement, especially when traffic load is beyond 500 Erlang. Under the random SCA scheme, the more FSs a request required, the more likely it is blocked for lacking enough contiguous FSs in one single core. Hence, there are few blocked requests which need the optimization of SSS-SCA in the condition where the requests require fewer FSs.

5 Conclusion

In this paper, spatial super-channel based SCA scheme is introduced in SDM optical networks. Simulation results show that the proposed SCA scheme is a promising scheme, which can reduce blocking probability and improve Resource Consumption Ratio all in 9-core, 12-core, 19-core MCFs.

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