Crosstalk-aware RCSA for spatial division multiplexing enabled elastic optical networks with multi-core fibers

Ruijie Zhu (朱睿杰)[1,2], Yongli Zhao (赵永利)[1], Hui Yang (杨 辉)[1], Haoran Chen (陈浩然)[1], Jie Zhang (张 杰)[1,*], and Jason P. Jue[2]

[1]*State Key Laboratory of Information Photonics and Optical Communication, Beijing University of Posts and Telecommunications, Beijing 100876, China*

[2]*University of Texas at Dallas, Texas 75080, USA*

**Corresponding author: lgr24@bupt.edu.cn*

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In this Letter, we propose two crosstalk-aware routing, core, and spectrum assignment (CA-RCSA) algorithms for spatial division multiplexing enabled elastic optical networks (SDM-EONs) with multi-core fibers. First, the RCSA problem is modeled, and then a metric, i.e., CA spectrum compactness (CASC), is designed to measure the spectrum status in SDM-EONs. Based on CASC, we propose two CA-RCSA algorithms, the first-fit (FF) CASC algorithm and the random-fit (RF) CASC algorithm. Simulation results show that our proposed algorithms can achieve better performance than the baseline algorithm in terms of blocking probability and spectrum utilization, with FF-CASC providing the best performance.

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Currently, the emergence of heterogeneous and bandwidth-intensive applications, such as cloud computing and high definition video streaming, is placing a high flexibility requirement on optical networks. Enabled by orthogonal frequency division modulation (OFDM) technology and a sliceable bandwidth-variable transponder, elastic optical networks (EONs) can be a promising technique for these diverse applications[1]. In EONs, the optical spectrum is sliced into finer granularity, such as 6.25 or 12.5 GHz.

However, network traffic is expected to increase exponentially, and the transmission capacity of EONs based on a single-core fiber (SCF) is approaching its physical limitations[2]. To further increase network flexibility and capacity, the concept of EONs can be extended into the spatial domain, in which "spatial resources" can be flexibly assigned to different traffic demands. One approach for utilizing spatial resources is to deploy spatial-division multiplexing EONs (SDM-EONs)[2,3]. Experiments illustrated that a multi-core fiber (MCF) can be a promising candidate for SDM-EONs[4]. In SDM-EONs, the tremendous increment in transmission capacity must be combined with effective software defined networking (SDN) functionalities[5], guaranteeing flexible connection provisioning, efficient re-optimization solutions[6], and failure recovery techniques.

With the introduction of the spatial domain, the routing and spectrum assignment (RSA) problem[7–10] for EONs has to be extended to the routing, core, and spectrum assignment (RCSA) problem for SDM-EONs[11,12]. The RSA problem has been well studied in EONs; however, the RCSA problem is more challenging, and there are several new features in SDM-EONs, such as the mitigation of spectrum continuity constraint, which means that the signal can be exchanged from core to core freely while maintaining the same spectrum slice[13]. Furthermore, there is an additional physical constraint introduced by inter-core crosstalk. When the same spectrum slices overlap on the adjacent cores, crosstalk will occur. Because the crosstalk of different spectrum slices or non-adjacent cores is quite small, then it can be eliminated. However, the crosstalk between adjacent cores can severely impact the signal during the propagation process, so it is extremely important to consider crosstalk during the RCSA process. Note that crosstalk checking is a complex process. When a newly requested lightpath is provisioned, the physical layer impairment of both the new lightpath and other already provisioned lightpaths should satisfy a predefined threshold because the additional crosstalk caused by the new path may make the signal quality of the provisioned paths worse. Thus, it is extremely important to consider the crosstalk during the RCSA process, which is not considered in the standard RSA problem.

Several previous works have studied the RCSA problem. In Ref. [11], the RCSA problem was formulated using the integer linear programming (ILP) formulation. Tode *et. al.*, introduced the prioritized area concept, and two kinds of crosstalk-aware (CA) RCSA algorithms: the strict constraint and best-effort approaches[12]. However, these works just utilized a simple crosstalk check method to check the crosstalk of the new provisioned lightpath, and the crosstalk of the provisioned lightpaths were not maintained.

In this Letter, we propose two CA-RCSA algorithms for SDM-EONs with an MCF, i.e., the first-fit (FF) algorithm and the random-fit (RF) algorithm. We first introduce a model to solve the RCSA problem and analyze the intercore crosstalk. Then a metric named the CA spectrum compactness (CASC) measurement is designed. Based on CASC, FF-CASC and RF-CASC are proposed. The simulation results show that the proposed algorithms can achieve better performance than the FF algorithm in terms of blocking probability and spectrum utilization issue, and the FF-CASC yields the best performance.

The substrate network is modeled as a directed graph $G_s = (L_s, N_s, C_s)$, where L_s represents the set of optical links, N_s is the set of physical nodes, and C_s is the set of cores of each physical link. $L[l_{i,j}]$ is an adjacency matrix representing links of G_s, where $l_{i,j}$ is the link length of the link (i, j). The threshold of the crosstalk is defined as TH. For the RCSA problem, crosstalk must be taken into account. When a request is allocated with a lightpath on the physical network, the crosstalk of the lightpath should be calculated and guaranteed to be below TH. At the same time, the crosstalk of the established lightpaths should be maintained in case the allocated requests are seriously affected by the crosstalk. It is worth noting that we primarily consider the inter-core crosstalk in this Letter. Intra-core impairment is addressed through the introduction of a guardband between lightpaths.

To decrease the crosstalk and achieve a dense core arrangement, a trench-assisted MCF (TA-MCF) was developed[14]. Figure 1(a) shows a schematic diagram of the seven-core model used in this Letter, and the seven cores are numbered in a clockwise way. The schematic of a core with an index trench is shown in Fig. 1(b). To evaluate the statistical mean crosstalk of an MCF, we first exploit Eq. (1)[15]. Furthermore, the coupled-power theory is considered to form Eq. (2), where XT is the mean crosstalk[16].

$$h = \frac{2k^2 r}{\beta w_{tr}}. \tag{1}$$

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

In Eq. (1), h denotes the mean increase in crosstalk per unit length. k, r, β, and $w_{\rm th}$ are the relevant fiber parameters, representing the coupling coefficient, bend radius, propagation constant, and core pitch, respectively. In Eq. (2), n is the number of adjacent cores, and L represents the fiber length. From the crosstalk calculation equations, we note that the crosstalk is affected by the number of adjacent cores and the length of the fiber. It is obvious that the center core (core 6) can be seriously affected by the crosstalk, since it has six adjacent cores.

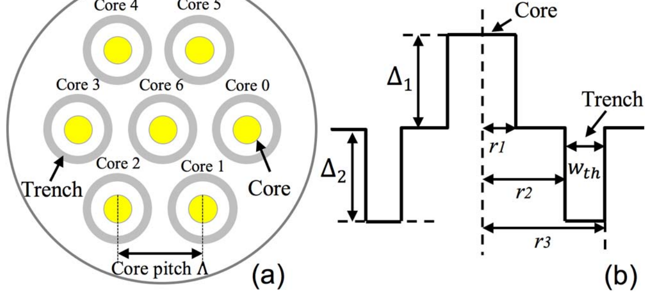

Fig. 1. (a) Schematic of TA-seven-core model; (b) schematic of a core with an index trench.

The available spectrum slots are utilized for the RCSA process, however, due to the crosstalk, there are several spectrum slots which cannot be used if the signal quality is to be maintained. To evaluate the spectrum status accurately, we propose a new metric, i.e., CASC. During the CASC measurement, when a newly requested path is provisioned, not only the crosstalk of the new lightpath should satisfy the predefined threshold, but the crosstalk of other already provisioned paths should also satisfy the quality requirement, since the additional crosstalk caused by the new path may make the signal quality of the provisioned paths worse.

We assume that there is a part of the spectrum resources available in core c over link l from the minimum spectrum slot $S_{\min}$ to the maximum spectrum slot $S_{\max}$. The total number of spectrum slots of this spectrum resource can be obtained as $S_{\max} - S_{\min} + 1$. The number of spectrum slots allocated for the $i_{\rm th}$ lightpath on this spectrum resources of core c over link l is represented as B_i^{cl}. So the total number of occupied spectrum slots is $\sum_{i=1}^{N} B_i^{cl}$, where N is the total number of established connections. Among the spectrum resources from $S_{\min}$ to $S_{\max}$, the available spectrum segments can be described as $(G_1^{cl}, G_2^{cl} \ldots G_j^{cl} \ldots G_g^{cl})$, where G_j^{cl} is the $j_{\rm th}$ available spectrum segment of this spectrum resource in core c over link l, and g is the total number of the spectrum segments. For a lightpath requiring one spectrum slot, we assign it to each segment G_j^{cl} from left to right to find all the possible allocation solutions. For each allocation solution, we calculate the corresponding crosstalk value using Eq. (2). The crosstalk of the overlapping established lightpaths of the adjacent cores will also be calculated. If either of the crosstalk values is larger than the threshold, this solution will be rejected. We then sum the number of spectrum slots of the $j_{\rm th}$ available spectrum segment and denote this sum as A_j^{cl}. The total suitable slots on the core c over link l is described as $\sum_{j=1}^{g} A_j^{cl}$, and the average available spectrum slots of these segments is defined as $\sum_{j=1}^{g} A_j^{cl}/g$. The CASC of core c over link l is defined as follows:

$$E^{cl} = \frac{S_{\max} - S_{\min} + 1}{\sum_{i=1}^{N} B_i^{cl}} \times \frac{\sum_{j=1}^{g} A_j^{cl}}{g}. \tag{3}$$

To illustrate the process of calculating SC, we provide an example, as shown in Fig. 2. There are four cores with the currently occupied spectrum slots shown as gray spectrum slots. We consider the allocation of a lightpath with one slot to available spectrum segments on core 1 and core 2, respectively. The red spectrum slots (A_1 of core 1 and A_4 of core 2) show infeasible spectrum allocations, because if these spectrum slots are used, the crosstalk of the

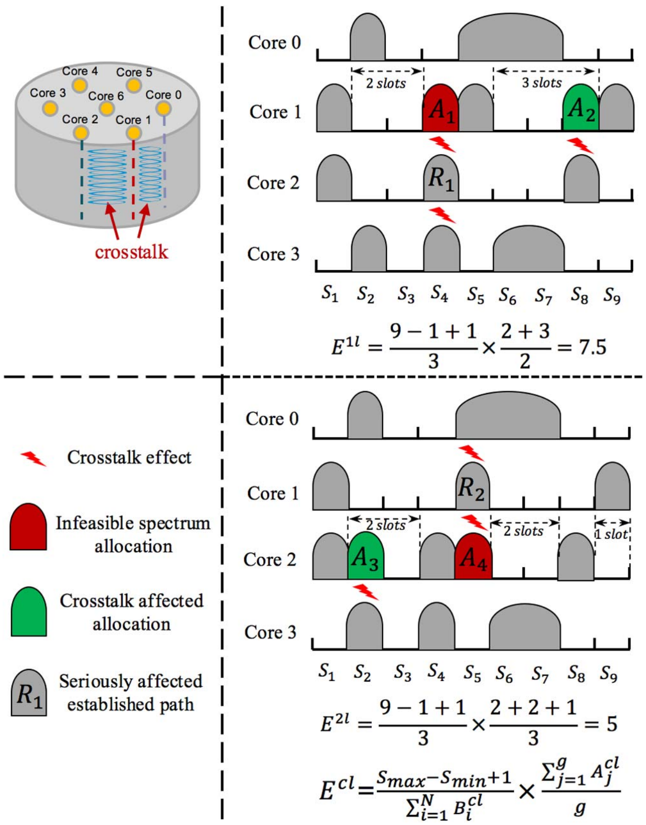

Fig. 2. CASC measurement.

established lightpaths of the adjacent cores calculated using Eq. (2) will exceed the threshold. The green spectrum slots (A_2 of core 1 and A_3 of core 2) show the spectrum allocations that are affected by the crosstalk, but their crosstalk and the crosstalk of the established lightpaths of the adjacent cores are below the threshold; thus, these slots are still applicable. Note that if we establish a lightpath utilizing the spectrum slot A_1, even though the crosstalk of newly provisioned lightpath can satisfy the signal quality requirement, the adjacent core of established lightpath R_1 will be seriously affected, and its crosstalk cannot fulfill the requirement. Thus, spectrum slot A_1 cannot be used to set up a lightpath. For the same reason, spectrum slot A_4 of core 2 cannot be utilized. For spectrum slot A_2 of core 1 and spectrum slot A_3 of core 2, both of them and the established lightpaths of their adjacent cores will be affected by the crosstalk, but their crosstalk does not exceed the threshold. Thus, spectrum slots A_2 and A_3 can be used.

To utilize the spectrum resources efficiently and to decrease the crosstalk, we propose two CA-RCSA algorithms based on CASC, the FF-CASC and the RF-CASC. The algorithms are divided into two stages, the FF or RF stage and the CASC stage.

First, the Dijkastra algorithm is applied to calculate the shortest path for the coming request. At the beginning, the network resources are not abundantly utilized, and there are many spectrum resources available. So a core is selected from core 0 to core 6 in the core set for the FF-CASC. If there are available spectrum resources on the selected core, we attempt to assign the request onto the spectrum slots based on the FF algorithm. Then the crosstalk will be calculated. If there are not enough spectrum resources or the crosstalk cannot be satisfied, we will jump to the CASC stage. In the CASC stage, the SC E^{cl} of each core of each link along the path is calculated. Then for each link, the core with the largest E^{cl} will be selected as the propagation core. The reason is that the CASC value of each core can reflect the spectrum status accurately when the crosstalk is taken into consideration, and when a request is routed on the core with a higher CASC value, there will be a higher chance for this request to be provisioned successfully. There may be several spectrum allocations on the selected core of each link along the path, and after the allocation of the request, the spectrum status will be changed. To evaluate the degree to which the allocation affects the spectrum state, we calculate E^{cl}_{before} before the request is allocated onto the spectrum segment of core c over link l. The SC of the selected cores of the links along the path is summed and defined as $\sum_{c\in C, l\in \text{path}} E^{cl}_{\text{before}}$. In the same way, after the allocation of the request, we obtain $\sum_{c\in C, l\in \text{path}} E^{cl}_{\text{after}}$. Then ΔE along this path can be obtained as follows:

$$\Delta E = \sum_{c\in C, l\in \text{path}} E^{cl}_{\text{before}} - \sum_{c\in C, l\in \text{path}} E^{cl}_{\text{after}}, \tag{4}$$

where ΔE is the reduction of SC on the selected core of each link along the path. We will choose the minimum ΔE, and its corresponding core selection and spectrum allocation, as the RCSA method. In this way, we can choose the best spectrum segment to allocate the request and leave as many spectrum resources as possible for the future requests considering the crosstalk. This approach will help to reduce the blocking probability. The difference between RF-CASC and FF-CASC is the first stage, and RF-CASC will select a core randomly (except core 6) and try to assign the request on this core along the path based on the FF strategy. The flowchart of the FF-CASC algorithm is shown in Fig. 3.

In the simulation, NSFNET (14 nodes, 21 links) is used as the simulation topology, with the assumption that each fiber has seven cores and each core has 100 spectrum slots. The fiber parameters k, r, β, and w_{th} are set as 3.16×10^{-5}, 55 mm, 4×10^{6}, 45 μm, respectively, and the threshold for the crosstalk is -32 dB[4]. The bandwidth requirements of the requests are uniformly distributed between two and seven spectrum slots. To avoid the linear and nonlinear intra-core impairments, one spectrum slot is assumed as the guardband between each lightpath. The simulated requests follow a Poisson process, where the arrival rate λ follows the Poisson distribution. The holding time of each request follows an exponential distribution with a mean value μ, and μ is set to be 0.1. The results are obtained from 10000 simulated requests. The normalized traffic load can be defined as follows: $\text{normTraffic} = (\lambda/\mu * hops * b)/(l * c * s)$, where $hops$ is

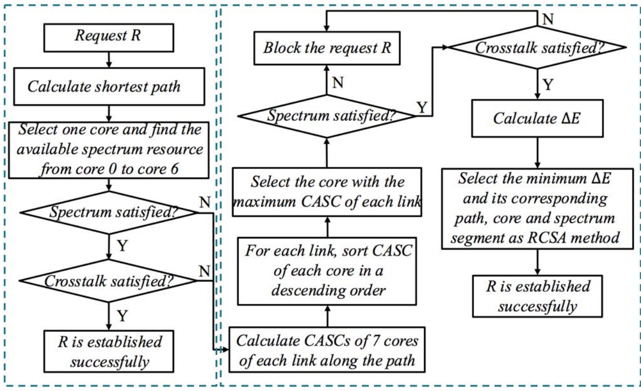

Fig. 3. FF-CASC algorithm.

the average number of hops of each request, b is the average bandwidth requirement in terms of the number of spectrum slots (the guardband is included), l is the number of physical fiber links, c is the number of cores per fiber, and s is the number of spectrum slots of each core. The parameters *hops*, b, l, c, and s are 2.1, 5.5, 21, 7, and 100, respectively. When λ/μ is 1000, the normalized traffic load is 0.78. When λ/μ is 2000, the normalized traffic load is 1.57. To evaluate the performance of the proposed algorithms, we proposed the FF-CA algorithm and the RF-CA as the baseline algorithms. In FF-CA, when the spectrum allocation found that using the FF algorithm cannot satisfy the crosstalk requirement, it will run FF again to find next possible spectrum allocation. If repeated attempts fail to find a valid spectrum allocation, then the request will be blocked. In RF-CA, the core will be randomly selected, except for core 6, in the core selected stage. In the spectrum allocation stage, when the spectrum allocation found that using the RF algorithm cannot satisfy the crosstalk requirement, it will run the RF again to find the next possible spectrum allocation.

The blocking probability performance[17] of the three RCSA algorithms are shown in Fig. 4. We can see that the proposed FF-CASC and RF-CASC algorithms can greatly reduce the blocking probability compared to the baseline algorithm. The baseline algorithm may result in blocking because of less spectrum resources or failure to fulfill the crosstalk requirement. However, the proposed algorithms will jump to the CASC stage. Then the spectrum status can be evaluated accurately based on CASC, and a suitable core will be selected on each link along the path. In the spectrum assignment process, we will leave as many spectrum resources as possible considering the crosstalk, thus, more requests can be successfully allocated. We also note that FF-CASC performs better than RF-CASC. The reason is that RF-CASC can select core 6 in some cases. Core 6 has the worst crosstalk performance, and it can also affect the other cores. Thus, FF-CASC can achieve better performance than RF-CASC.

The spectrum utilization performance of these three RCSA algorithms is shown in Fig. 5. We note that FF-CASC performs the best. The reason is that, based on CASC, the requests can be allocated on the cores and the spectrum segments accurately, which result in less fragmentation and lower crosstalk.

The spectrum utilization of each core of the FF-CASC and RF-CASC are illustrated in Figs. 6 and 7, respectively. For FF-CASC, we can see that the core 0 and core 1 can achieve higher utilization than other cores.

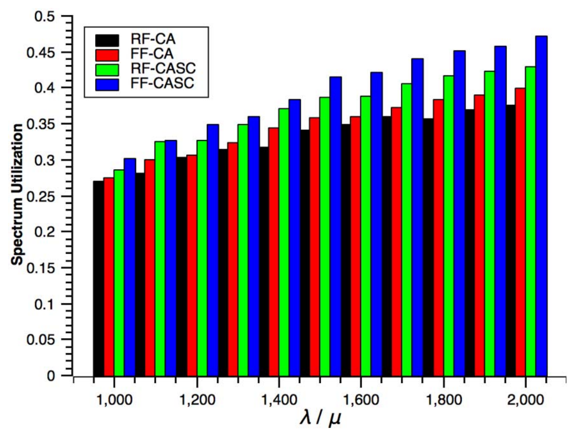

Fig. 5. Spectrum utilization performance.

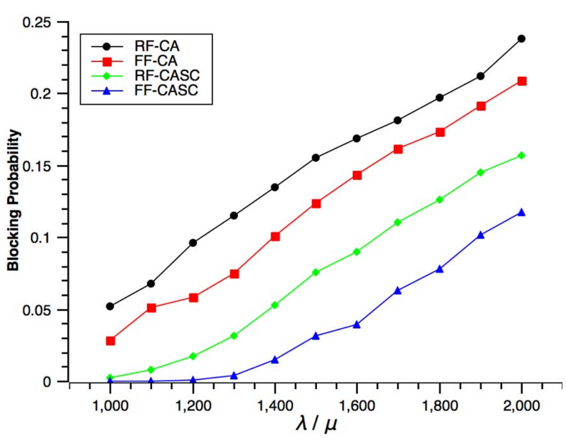

Fig. 4. Blocking probability performance.

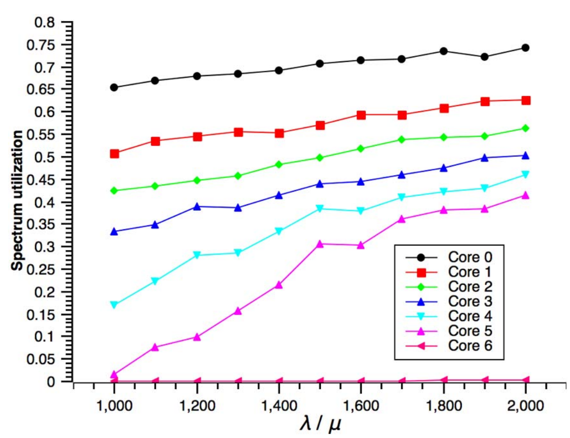

Fig. 6. Spectrum utilization of each core (FF-CASC).

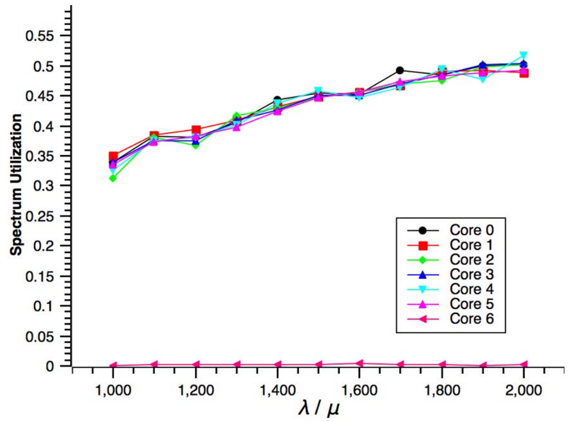

Fig. 7. Spectrum utilization of each core (RF-CASC).

The reason is that, in the first stage, core 0 and core 1 will be selected first. When these cores are thoroughly utilized, other cores will be selected. For RF-CASC, the cores will be selected randomly, and the utilization of core 0 to core 5 is almost the same as that shown in Fig. 7. Core 6 performs the worst considering the crosstalk, where in the CASC stage, core 6 is seldom selected. So, the utilization of core 6 is the least.

In conclusion, we propose two CA-RCSA algorithms in SDM-EONs with MCFs, i.e., FF-CSCA and RF-CSCA, which are based on the CASC measurement. Simulation results show that both of the proposed algorithms can achieve better performance than the FF algorithm, and FF-CASC performs the best.

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