Crosstalk-Aware Shared Backup Path Protection in Multi-Core Fiber Elastic Optical Networks

Fengxian Tang, Gangxiang Shen, *Senior Member, IEEE*, and George N. Rouskas, *Fellow, IEEE*

***Abstract*—Elastic optical networks employing multi-core fibers (MCF-EON) have the potential to expand significantly the transmission capacity of optical transport. However, wide deployment of such networks depends on addressing effectively two critical challenges: inter-core crosstalk, which may cause serious signal performance degradation in an MCF link, and survivability against network failures that may cause enormous data loss. In this article, we consider the design of MCF-EONs with shared-backup path protection (SBPP), one of the most efficient techniques for protecting network traffic. Specifically, we tackle the crosstalk-aware routing, core, and spectrum assignment (CA-RCSA) problem with the objective of jointly minimizing the network spectrum resources used and the total inter-core crosstalk. We formulate the problem as an integer linear programming (ILP) model subject to strict inter-core crosstalk limits for each provisioned lightpath, and we also propose an auxiliary graph (AG) based heuristic algorithm for lightpath provisioning. Simulation studies show that our algorithm is effective in terms of the objectives, and it is efficient to perform close to the ILP model in small networks, for which solving the ILP is feasible.**

***Index Terms*—Inter-core crosstalk, MCF-EON, RCSA, SBPP, survivability.**

I. Introduction

ELASTIC optical networks (EONs) support flexible network bandwidth allocation and efficient spectrum utilization and are being deployed to meet the ever-increasing capacity demand for optical transport [1]. A single standard single mode fiber (SSMF) generally only carries optical signals in the C band, and its transmission capacity is limited to about 100 Tb/s [2]. To further increase the capacity of a network, space division multiplexing (SDM) may be employed and has been widely studied [3]. Multi-core fiber (MCF) technology is considered as one of the most practical solutions to realize SDM due to its relative maturity [4]. While adopting MCF technology has the potential to overcome the capacity limit of the conventional optical network, inter-core crosstalk between lightpaths has emerged as a critical challenge for MCF-EONs. Inter-core crosstalk may severely degrade the quality of optical signals transmitted in two neighboring fiber cores, potentially countering the advantages of MCF technology. Consequently, extensive studies have been carried out to assign fiber cores and spectrum resources when provisioning lightpaths in MCF-EONs so as to alleviate inter-core crosstalk [5].

A second challenge has to do with network protection. A single-link failure in an MCF-EON will disable all fiber cores and hence will affect significantly more traffic than in a traditional SSMF-based optical network. But while network protection is even more important for an MCF-EON, provisioning additional backup lightpaths further complicates the task of mitigating the impact of inter-core crosstalk. Therefore, network protection in the context of MCF-EONs must invariably account for the presence of crosstalk.

Shared-backup path protection (SBPP) is an efficient protection technique as it allows for sharing of spare capacity among protection lightpaths [6] and it has been studied in the context of SDM-EONs [7]. Nevertheless, to the best of our knowledge, no study has jointly addressed the dual challenges of inter-core crosstalk and network protection in MCF-EONs. In this study, we focus on such a joint optimization effort by considering both spectrum resources and inter-core crosstalk in the provisioning of SBPP-based MCF-EONs. Specifically, we consider the crosstalk-aware routing, spectrum, and core assignment (CA-RCSA) problem in an SBPP-based MCF-EON and make several contributions. First, we use an analytical model to estimate inter-core crosstalk and impose a strict crosstalk threshold for each established lightpath. Second, we jointly optimize network capacity (spectrum) utilization and network-wide inter-core crosstalk in the context of SBPP. We develop an ILP optimization model for the survivable CA-RCSA problem, as well as a heuristic algorithm that establishes each lightpath by selecting MCF cores and spectra in a crosstalk-aware manner. Simulation studies indicate that the proposed survivable CA-RCSA approach is efficient both in reducing inter-core crosstalk and in improving network capacity utilization.

The rest of this paper is organized as follows. In Section II, we review related work on inter-core crosstalk reduction and network protection in an SDM optical network. In Section III, we discuss inter-core crosstalk estimation and SBPP in an

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Fengxian Tang and Gangxiang Shen are with the Suzhou Key Laboratory of Advanced Optical Communication Network Technology, and with the School of Electronic and Information Engineering, Soochow University, Suzhou 215006, China (e-mail: 20174028003@stu.suda.edu.cn; shengx@suda.edu.cn).

George N. Rouskas is with the Department of Computer Science, North Carolina State University, Raleigh, NC 27695 USA, and also with King Abdulaziz University, Jeddah, Saudi Arabia (e-mail: rouskas@ncsu.edu).

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TABLE I
LITERATURE OF DIFFERENT APPROACHES TO HANDLING INTER-CORE CROSSTALK

Crosstalk approach	References
Best-effort	[8-10]
Best-effort avoidance	[11-13]
Best-effort core prioritization	[14-19]

TABLE II
LITERATURE OF PROTECTION IN AN SDM OPTICAL NETWORK

Protection approach	References
***p*-Cycles**	[21-23]
DDP	[24, 25, 32]
SBPP	[26-32]

MCF-EON. We present an ILP model and a heuristic algorithm for the survivable CA-RCSA problem in Sections IV and V, respectively. We evaluate the proposed approach in Section VI and conclude the paper in Section VII.

II. RELATED WORK

A. Inter-Core Crosstalk in MCF Optical Networks

Inter-core crosstalk significantly impacts the signal transmission quality in an MCF-EON [3], so it is imperative to address this issue when provisioning lightpaths. There are two main approaches to handling inter-core crosstalk: (1) *best-effort* and (2) *strictly constrained*; the former may be further divided into two sub-classes, *best-effort core prioritization* and *best-effort avoidance*. Table I summarizes these three approaches to handling inter-core crosstalk in the literature. The best-effort avoidance approach attempts to minimize inter-core crosstalk between adjacent cores when establishing a new lightpath. This approach is widely used in the MCF optical network and different strategies and scenarios are considered, e.g., fragmentation avoidance strategy [8], SBPP-based network survivability [9], and programmable filterless optical network [10].

The best-effort core prioritization approach has a similar objective, but it additionally implements a dedicated core prioritization mechanism, whereby cores are considered for assignment to a lightpath in decreasing order of priority. Specifically, the priority of each core is determined by the extent to which it may reduce the dominant inter-core crosstalk: the higher the reduction in inter-core crosstalk, the higher the priority of a core. This approach is also widely used in the MCF optical network and different network scenarios are considered, e.g., architecture on demand (AoD) [11], bi-directional transmission [12], and routing, spectrum, and core and/or mode assignment (RSCMA) in an SDM-EON [13].

The strictly constrained approach estimates the inter-core crosstalk of each lightpath in advance, and establishes it only if the inter-core crosstalk between all the lightpaths is below a predefined threshold. In the context of this approach, some studies proposed crosstalk-aware lightpath provisioning algorithms to achieve efficient resource utilization in MCF-EON [14], [15]. And some studies employed this approach to evaluate the performance of different optimization strategies, e.g., fragmentation measurement [16], lightpath counter-propagation [17], machine learning [18], and traffic grooming [19].

B. Protection in SDM Network

Protection in SDM networks is a well-studied problem. Table II summarizes three protection approaches in the literature. Failure independent path protection (FIPP) *p*-Cycles are employed to efficiently provision survivable lightpath services in an SDM optical network [21]–[23]. Also, because of simplicity, dedicated path protection (DPP) is employed to provision survivable lightpath services in an SDM optical network [24], [25]. However, DPP is not efficient in terms of network resource utilization because dedicated protection capacity needs to be reserved for each survivable service.

To improve network resource utilization, the more efficient protection technique SBPP can be employed to protect an SDM optical network. SBPP allows different protection lightpaths to share protection resources on their common link(s) if their corresponding working lightpaths do not share any common link. Since SBPP is the protection technique we consider in this study, we next review related works that apply SBPP in the context of EONs.

For the conventional SBPP-based EON, Walkowiak and Klinkowski studied a static routing and spectrum assignment (RSA) problem by developing an integer linear programming (ILP) model and proposing efficient heuristic algorithms [26]. Also, Wang *et al.* studied the dynamic RSA problem for an SBPP-based EON [27]. For an SDM optical network, related studies have also been conducted. Oliveira and Fonseca proposed a novel routing, modulation level, and spectrum assignment (RMLSA) algorithm to generate primary and backup paths allowing for shared backup resource sharing and adaptive modulation format allocation in an SDM-EON [28]. They also developed three survivable RCSA algorithms by employing SBPP, FIPP p-Cycles and FIPP p-Cycles with priorities strategy in an SDM-EON [29]. Zhang *et al.* studied the SBPP-based virtual network (VN) mapping problem and proposed an algorithm called minimum free frequency slots (MFFS) mapping to improve spectrum efficiency in an SDM optical network [30]. Lin *et al.* applied SBPP together with ring cover to improve resource utilization of an MCF-EON [31]. Finally, Goscien and Walkowiak studied DPP and SBPP jointly in an SDM optical network by formulating ILP models for both survivable schemes and considering two SDM switching policies, i.e., independent switching and joint switching [32].

C. Summary

Based on our review of the literature, most studies of MCF-EON tackle the inter-core crosstalk and network protection aspects separately. Furthermore, the two studies [7], [28] that address SBPP in MCF-EON focus on network resource utilization, and do not attempt to minimize inter-core crosstalk, which is however important for operating MCF-EONs. To close this gap, in this study we carry out a comprehensive study on SBPP-based MCF-EONs with the objective of optimizing both resource utilization and inter-core crosstalk. Therefore, our work represents

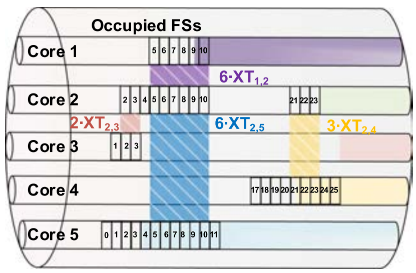


Fig. 1. Inter-core crosstalk in a 5-core MCF.

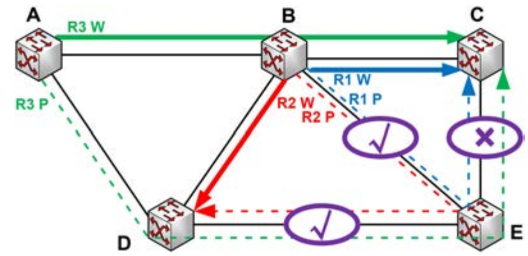


Fig. 2. Concept of SBPP in an MCF-EON.

a practical approach to deploying the promising features of SBPP while respecting the inter-core crosstalk constraints in MCF-EONs.

III. Inter-Core Crosstalk Estimation and SBPP in MCF-EON

A. Model for Inter-Core Crosstalk Estimation in an MCF

According to [16], the inter-core crosstalk $XT_{i,j}$ between cores i and j in an MCF can be calculated by (1), where $h_{i,j}$ is power coupling coefficient and L is fiber length. Quantity $h_{i,j}$ can be further calculated by (2), where br and β represent bending radius and propagation constant, respectively whereas, $k_{i,j}$ and $\Lambda_{i,j}$ represent coupling coefficient and core pitch between cores i and j, respectively. According to the optical waveguide theory, mode coupling coefficient $k_{i,j}$ is calculated by (3), where Δ is relative refractive index difference, cr is core radius, U and W are normalized transverse wave numbers in the core and cladding, respectively, and V is normalized frequency. Moreover, since inter-core crosstalk occurs only between lightpaths in different cores that use the same spectrum, we can use (4) to calculate the overall inter-core crosstalk for specific core i, where $\boldsymbol{F}$ is the set of frequency slots (FSs) considered, $\boldsymbol{C}$ represents the set of cores in this MCF, and $\delta_{i,j}^{f}$ is a binary value that denotes whether FS f is used by existing lightpaths in both cores i and j. Fig. 1 shows a 5-core MCF as an example, where the total inter-core crosstalk of core 2 can be calculated as $XT_2^F = 6 \cdot XT_{12} + 2 \cdot XT_{23} + 3 \cdot XT_{24} + 6 \cdot XT_{25}$.

$$XT_{i,j} = \tanh\left(h_{i,j} \cdot L\right) \tag{1}$$

$$h_{i,j} = \frac{2 \cdot k_{i,j}^2 \cdot br}{\beta \cdot \Lambda_{i,j}} \tag{2}$$

$$\kappa_{i,j} = \frac{\sqrt{\Delta}}{cr} \cdot \frac{U^2}{V^3} \cdot \frac{K_0\left(\frac{\Lambda_{i,j}}{cr} \cdot W\right)}{K_1^2\left(W\right)} \tag{3}$$

$$XT_i^{\boldsymbol{F}} = \sum_{f \in \boldsymbol{F}, j \in \boldsymbol{C}: j \neq i} XT_{i,j} \cdot \delta_{i,j}^{f} \tag{4}$$

B. SBPP in an MCF-SDM Network

SBPP allows protection resources to be shared among multiple protection lightpaths as long as their corresponding working lightpaths are link-disjoint. Fig. 2 shows an example of SBPP protection in an MCF-EON with three different lightpath services, R1, R2, and R3. Each service is assigned one working and one protection lightpath that are link-disjoint. In Fig. 2, working lightpaths are represented with solid lines and protection lightpaths with dotted lines: B-C and B-E-C for R1, B-D and B-E-D for R2, and A-B-C and A-D-E-C for R3. Since the working lightpaths of R1 and R2 do not share any common link, their corresponding protection lightpaths may share protection resources on their common link B-E. Similarly, the resources on the common link D-E can also be shared by the protection lightpaths of R1 and R2, because their working lightpaths are link-disjoint. On the other hand, since the working lightpaths of R1 and R3 share link B-C, the resources on their common protection link E-C cannot be shared.

IV. Crosstalk-Aware Routing, Core, and Spectrum Assignment (CA-RCSA) in an SBPP-Based MCF-EON

We consider the crosstalk-aware routing, core, and spectrum assignment (CA-RCSA) problem in an SBPP-based MCF-EON. In this section, we first define this problem, and then develop a corresponding ILP formulation.

A. Problem Statement

We define the CA-RCSA problem in an SBPP-based MCF-EON as follows.

Given:

1) A general network topology represented by a graph $G(\boldsymbol{N}, \boldsymbol{L})$, where $\boldsymbol{N}$ is the set of nodes and $\boldsymbol{L}$ is the set of fiber links connecting the nodes in $\boldsymbol{N}$;
2) A set of lightpath demands given *a priori*.
3) A working path and a set of protection paths for each lightpath demand, such that the working path of a demand is link-disjoint from all its protection paths.

Constraints:

1) Demand serving constraint: a working and protection lightpath must be established for each given demand.
2) Core constraint: the number of cores in each MCF is limited (fixed).
3) Core capacity constraint: the number of FSs in each core is limited.
4) Spectrum contiguity: the set of FSs allocated to each lightpath must be spectrally contiguous.
5) Spectrum continuity: the set of contiguous FSs allocated to each lightpath must occupy the same part of spectrum on each link traversed by the lightpath.

6) Spectrum non-overlap: lightpaths using the same core must use parts of spectrum that do not overlap.
7) Crosstalk constraint: the crosstalk of each established lightpath must be no greater than a specific threshold.

Objective:

Minimize the total number of MCF cores used and the inter-core crosstalk between established lightpaths subject to all the above constraints.

B. ILP Model

We now present an ILP formulation for CA-RCSA.

Sets:

$\boldsymbol{L}$ Set of network links.
$\boldsymbol{C}$ Set of cores in each MCF.
$\boldsymbol{NR}$ Set of node pairs in the MCF-EON.
$\boldsymbol{P_r}$ Set of protection paths for the node pair $r \in \boldsymbol{NR}$.
$\boldsymbol{WL_r}$ Set of links along the working lightpath between node pair $r \in \boldsymbol{NR}$.
$\boldsymbol{B_r^p}$ Set of links along the protection lightpath $p \in \boldsymbol{P_r}$.

Parameters:

d_r Number of FSs required by demand r.
$d'_{r,p}$ Number of FSs required by demand r if its protection lightpath is established along protection path p. Here we assume that the number of FSs is given in advance, which is derived from the actual user capacity demand. Specifically, for the working path, the number of FSs is derived as the actual user capacity demand divided by the spectrum efficiency of the most efficient modulation format adopted by the working path. The modulation format is chosen according to the physical distance of the working path. The same derivation can be made for the number of FSs on protection path *p*, which is also the actual user capacity demand divided by the spectrum efficiency of the most efficient modulation format of path *p*.
$\Lambda_{i,j}^l$ Inter-core crosstalk between core s i and j on link *l*.
η_l^r A binary parameter that equals 1 if the working path of node pair *r* traverses link *l*; 0, otherwise.
$\zeta_{r,p}^l$ A binary parameter that equals 1 if the protection path *p* of node pair *r* traverses link *l*; 0, otherwise.
$\varepsilon_{r1,r2}$ A binary parameter that equals 1 if the working paths of node pairs $r1$ and $r2$ share common link(s); 0, otherwise.
$\epsilon_{r1,r2}^p$ A binary parameter that equals 1 if the working path of node pair $r1$ and protection path p of node pair $r2$ share common link(s); 0, otherwise.
$\xi_{r1,r2}^{p1,p2}$ A binary parameter that equals 1 if protection path $p1$ of node pair $r1$ and protection path $p2$ of node pair $r2$ share common link(s); 0, otherwise.
M A large value.
α A weight factor.
Ξ A predefined inter-core crosstalk threshold.
W The maximum index of FSs that each core carries.

Variables:

S_r An integer variable denoting the starting (lowest) FS index of the working lightpath (established) between node pair *r*.
$S'_{r,p}$ An integer variable denoting the starting FS index of the protection lightpath between node pair *r* when it is established along protection path *p*.
E_r An integer variable denoting the ending (highest) FS index of the working lightpath (established) between node pair *r*.
$E'_{r,p}$ An integer variable denoting the ending FS index of the protection lightpath between node pair *r* if it is established along protection path *p*.
X_p^r A binary variable that equals 1 if protection path p of node pair r is chosen for establishing the protection lightpath of the node pair; 0, otherwise.
U_l^i A binary variable that equals 1 if core *i* of link *l* is used; 0, otherwise.
$\Gamma_{r1,r2}$ A binary variable that equals 1 if the working lightpath starting index of $r1$ is larger than that of $r2$, i.e., $S_{r1} > S_{r2}$; 0, otherwise.
$H_{r1,r2}^{p2}$ A binary variable that equals 1 if the working lightpath starting index of $r1$ is larger than the protection lightpath starting index of node pair $r2$ that is established along protection path *p2*, i.e., $S_{r1} > E_{r2,p2}$; 0, otherwise.
$N_{r1,r2}^{p1,p2}$ A binary variable that equals 1 if the protection lightpath starting index of $r1$ that is established along protection path *p1* is larger than the protection index of node pair $r2$ that is established along protection path *p2*, i.e., $S_{r1} > E_{r2,p2}$; 0, otherwise.
$O_r^{l,i}$ A binary variable that equals 1 if core *i* of link *l* is used for establishing a working lightpath between node pair *r*; 0, otherwise.
$O'^{l,i}_{r,p}$ A binary variable that equals 1 if core *i* of link *l* is used for establishing a protection lightpath between node pair *r* with protection path p; 0, otherwise.
β_r^k A binary variable that equals 1 if $k \geq S_r$, where k is an FS index; 0, otherwise.
γ_r^k A binary variable that equals 1 if $k \leq E_r$, where k is an FS index; 0, otherwise.
$\beta'^k_{r,p}$ A binary variable that equals 1 if $\geq S'_{r,p}$, where k is an FS index; 0, otherwise.
$\gamma'^k_{r,p}$ A binary variable that equals 1 if $k \leq E'_{r,p}$, where k is an FS index; 0, otherwise.
$\theta_{l,r}^{i,k}$ A binary variable that equals 1 if FS k in core *i* of link *l* has been used for establishing the working lightpath of node pair r; 0, otherwise.
$\theta'^{i,k}_{l,r,p}$ A binary variable that equals 1 if FS k in core *i* of link *l* has been used for establishing the protection lightpath of node pair r; 0, otherwise.
$\omega_l^{i,k}$ A binary variable that equals 1 if FS k in core *i* of link *l* has been used; 0, otherwise.
$A_{k,l}^{i,j}$ A binary variable that equals 1 if FS k is used for lightpath establishment in both core i and core j of link; 0, otherwise.

Objective:

$$\text{Minimize} \sum_{l\in\boldsymbol{L},i\in\boldsymbol{C}} U_l^i + \alpha \cdot \sum_{l\in\boldsymbol{L},i,j\in\boldsymbol{C},0\le k\le \mathrm{W},i\ne j} A_{k,l}^{i,j}\cdot\Lambda_{i,j}^l \quad (5)$$

Objective function (5) consists of two terms: the total number of MCF cores used to satisfy all demands (primary objective) and the total inter-core crosstalk between lightpaths in the entire network (secondary objective). The weight factor α in (5) is set to a small value, i.e., 0.01, so that the objective function gives priority to minimizing the first term. If there are multiple solutions with the same value for the primary objective, then the objective function forces the selection of the solution with the lowest total inter-core crosstalk (note also that the crosstalk constraint ensures that all lightpaths meet the inter-core crosstalk threshold). Note that the above bi-criteria objective is valid for an uncoupled MCF. For a coupled MCF, the solutions with the same number of core usage can be different when different sets of cores are used. In this case, a different objective function should be formulated.

Subject to:

–Protection path selection

$$\sum_{p\in\boldsymbol{P_r}} X_p^r = 1\ \forall r\in\boldsymbol{NR} \quad (6)$$

–FS contiguity

$$E_r - S_r - d_r + 1 = 0\ \forall r\in\boldsymbol{NR} \quad (7)$$

$$E'_{r,p} - S'_{r,p} - d'_{r,p} + 1 \le M\cdot\left(1-X_p^r\right)\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r} \quad (8)$$

$$E'_{r,p} - S'_{r,p} - d'_{r,p} + 1 \ge -M\cdot\left(1-X_p^r\right)\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r} \quad (9)$$

$$E_r \le W\ \forall r\in\boldsymbol{NR} \quad (10)$$

$$E'_{r,p} \le W\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r} \quad (11)$$

–FS non-overlapping

$$\Gamma_{r1,r2} + \Gamma_{r2,r1} = 1\ \forall r1,r2\in\boldsymbol{NR}, r1\ne r2 \quad (12)$$

$$E_{r2} - S_{r1} \le M\cdot\left(\Gamma_{r1,r2} + 1 - O_{r1}^{l,i} + 1 - O_{r2}^{l,i}\right) - 1\ \forall r1,r2\in\boldsymbol{NR}, i\in\boldsymbol{C}, l\in\boldsymbol{WL_{r1}}\cap\boldsymbol{WL_{r2}}, r1\ne r2 \quad (13)$$

$$E_{r1,r2}^{p2} + E_{r2,r1}^{p1} = 1\ \forall r1,r2\in\boldsymbol{NR}, p1\in\boldsymbol{P_{r1}}, p2 \in\boldsymbol{P_{r2}}, r1\ne r2 \quad (14)$$

$$E'_{r2,p2} - S_{r1} \le M \cdot\left(E_{r1,r2}^{p2} + 1 - O_{r1}^{l,i} + 1 - {O'}^{l,i}_{r2,p2} + 1 - X_{p2}^{r2}\right) - 1\ \forall r1,r2 \in\boldsymbol{NR}, p2\in\boldsymbol{P_{r2}}, i\in\boldsymbol{C}, l\in\boldsymbol{WL_{r1}}\cap\boldsymbol{B_{r2}^{p2}}, r1\ne r2 \quad (15)$$

$$N_{r1,r2}^{p1,p2} + N_{r2,r1}^{p2,p1} = 1\ \forall r1,r2\in\boldsymbol{NR}, p1 \in\boldsymbol{P_{r1}}, p2\in\boldsymbol{P_{r2}}, r1\ne r2 \quad (16)$$

$$E'_{r2,p2} - S'_{r1,p1} \le M\cdot\Big(N_{r1,r2}^{p1,p2} + 1 - {O'}^{l,i}_{r1,p1} + 1 - {O'}^{l}_{r2,p2,i} + 1 - X_{p1}^{r1} + 1 - X_{p2}^{r2} + 1 - \xi_{r1,r2}^{p1,p2}\Big) - 1\ \forall r1,r2\in\boldsymbol{NR}, i\in\boldsymbol{C}, l\in\boldsymbol{B_{r1}^{p1}}\cap\boldsymbol{B_{r2}^{p2}}, r1\ne r2 \quad (17)$$

–Fiber core assignment

$$\sum_{i\in\boldsymbol{C}} O_r^{l,i} = 1\ \forall r\in\boldsymbol{NR}, l\in\boldsymbol{WL_r} \quad (18)$$

$$\sum_{i\in\boldsymbol{C}} {O'}^{l,i}_{r,p} - 1 < M\cdot\left(1-X_p^r\right)\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, l\in\boldsymbol{B_r^p} \quad (19)$$

$$\sum_{i\in\boldsymbol{C}} {O'}^{l,i}_{r,p} - 1 \ge -M\cdot\left(1-X_p^r\right)\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, l\in\boldsymbol{B_r^p} \quad (20)$$

$$U_l^i \ge O_r^{l,i}\ \forall r\in\boldsymbol{NR}, i\in\boldsymbol{C},\ l\in\boldsymbol{L} \quad (21)$$

$$U_l^i \ge {O'}^{l,i}_{r,p}\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, i\in\boldsymbol{C},\ l\in\boldsymbol{L} \quad (22)$$

$$k - S_r \le M\cdot\beta_r^k\ \forall r\in\boldsymbol{NR}, 1\le k\le W \quad (23)$$

$$E_r - k \le M\cdot\gamma_r^k\ \forall r\in\boldsymbol{NR}, 1\le k\le W \quad (24)$$

$$k - S'_{r,p} \le M\cdot{\beta'}^{k}_{r,p}\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, 1\le k\le W \quad (25)$$

$$E'_{r,p} - k \le M\cdot{\gamma'}^{k}_{r,p}\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, 1\le k\le W \quad (26)$$

$$1 - \theta_{l,r}^{i,k} \le M\cdot\left(3 - \beta_r^k - \gamma_r^k - O_r^{l,i}\right)\ \forall r\in\boldsymbol{NR},\ l\in\boldsymbol{WL_r}, i\in\boldsymbol{C}, 1\le k\le W \quad (27)$$

$$1 - {\theta'}^{i,k}_{l,r,p} \le M\cdot\left(3 - {\beta'}^{k}_{r,p} - {\gamma'}^{k}_{r,p} - {O'}^{l,i}_{r,p}\right)\ \forall r\in\boldsymbol{NR}, p\in\boldsymbol{P_r}, l\in\boldsymbol{B_r^p}, i\in\boldsymbol{C}, 1\le k\le W \quad (28)$$

$$\omega_l^{i,k} \ge \theta_{l,r}^{i,k}\ \forall r\in\boldsymbol{NR}, l\in\boldsymbol{WL_r}, i\in\boldsymbol{C}, 1\le k\le W \quad (29)$$

$$\omega_l^{i,k} \ge {\theta'}^{i,k}_{l,r,p}\ \forall r\in\boldsymbol{NR}, l\in\boldsymbol{P_r}, i\in\boldsymbol{C}, p\in\boldsymbol{P_r}, 1\le k\le W \quad (30)$$

$$\omega_l^{i,k} \le \theta_{l,r}^{i,k} + {\theta'}^{i,k}_{l,r,p}\ \forall r\in\boldsymbol{NR}, l\in\boldsymbol{P_r}, p \in\boldsymbol{P_r}, i\in\boldsymbol{C}, 1\le k\le W \quad (31)$$

–Inter-core crosstalk limitation

$$1 - A_{k,l}^{i,j} \le M\cdot\left(2 - \omega_l^{i,k} - \omega_l^{j,k}\right)\ \forall r\in\boldsymbol{NR}, l \in\boldsymbol{L}, i,j\in\boldsymbol{C}, 1\le k\le W, i\ne j \quad (32)$$

$$\sum_{l\in\boldsymbol{WL_r},i,j\in C,i\ne j} \Lambda_{i,j}^l\cdot A_{k,l}^{i,j}\cdot\theta_{l,r}^{i,k} \le \Xi\ \forall r\in\boldsymbol{NR}, 1\le k\le W \quad (33)$$

$$\sum_{l\in\boldsymbol{B_r^p},i,j\in C,i\ne j} \Lambda_{i,j}^l\cdot A_{k,l}^{i,j}\cdot{\theta'}^{i,k}_{l,r,p} \le \Xi\ \forall r\in\boldsymbol{NR}, 1\le k\le W \quad (34)$$

Protection path selection: Constraint (6) ensures that only one protection path is selected for establishing the protection lightpath between a pair of nodes.

FS contiguity: Constraint (7) ensures that each working lightpath is assigned a block of contiguous FSs equal to the corresponding demand. Constraints (8) and (9) are similar but related to the specific path selected for establishing a protection lightpath. Constraints (10) and (11) ensure that the ending FS index of any lightpath must be no greater than the maximum index that one core can carry.

FS non-overlap: Constraints (12) and (13) ensure that two working lightpaths using the same core do not overlap in spectrum. Constraints (14) and (15) are similar but related to a working lightpath and a protection lightpath that share the same core. Constraints (16) and (17) are also similar but related to two protection lightpaths whose corresponding working paths share common links.

Fiber core assignment: Constraint (18) ensures that only one core in a link traversed by a working lightpath is selected for establishing the working lightpath. Constraints (19) and (20) ensure that only one core in a link traversed by a protection lightpath is selected for establishing the protection lightpath. Constraints (21) and (22) indicate that a core in a link is used if it has been assigned for establishing a working or protection lightpath. Constraints (23)–(26) jointly check whether FS k is used by an established working or protection lightpath. Constraints (27)–(31) jointly check whether FS k is used in a fiber core.

Inter-core crosstalk: Constraint (32) determines whether an FS is used in two adjacent fiber cores. Constraints (33) and (34) ensure that the inter-core crosstalk for an established lightpath does not exceed a predefined inter-core crosstalk threshold Ξ.

V. Heuristic Algorithm for RSCTA Problem

Since the CA-RCSA problem is NP-complete [33], we cannot expect to solve the ILP model to optimality within a reasonable time even for medium-size networks. Therefore, we now present an efficient heuristic algorithm to obtain near-optimal solutions in polynomial time. The algorithm employs the concept of spectrum window (SW) [27] to satisfy the contiguity and continuity constraints when allocating spectrum resources to lightpaths.

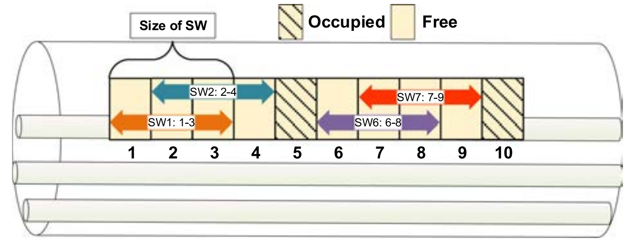


Fig. 3. Spectrum windows (SWs) in a fiber core.

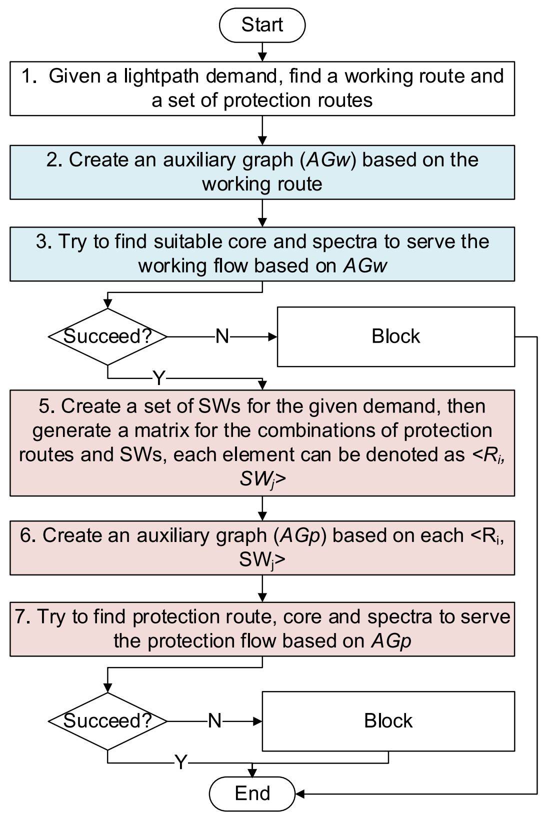


Fig. 4. Flowchart of CA-RCSA in an SBPP-based MCF-EON.

A. Spectrum Window (SW)

The spectrum contiguity constraint requires that all FSs of a lightpath be spectrally consecutive. In this study, we apply the concept of spectrum window (SW) [27] to enforce this constraint. Each SW represents a block of consecutive FSs whose size is equal to the bandwidth required by a particular demand. Fig. 3 shows an example of SWs created in a fiber core. We assume that an MCF core carries a total of 10 FSs and the size of each SW is 3 FSs. The SW is available only if all the contained FSs are free; otherwise, it is not available. In the above example, only SW1, 2, 6 and 7 are available.

The spectrum continuity constraint requires that the block of FSs allocated to a lightpath is the same on all fiber links traversed by the lightpath. Therefore, we choose the same SW on each link along a route [34] to enforce this constraint.

B. Crosstalk-Aware Routing, Spectrum, and Core Assignment

We provision lightpath services in an SBPP-based MCF-EON by considering the demands sequentially. For each demand, we create an auxiliary graph (AG) to select a suitable working-protection path pair, core and spectrum block with the minimum inter-core crosstalk. Fig. 4 illustrates the flowchart of this AG-based CA-RCSA algorithm for a given demand.

In Step 1, we route the working lightpath of the given demand along the shortest route between the corresponding node pair. We then use the depth-first search (DFS) algorithm to find a set of candidate protection routes $\boldsymbol{R}$ between the same node pair. These protection routes are link-disjoint from the working route.

In Step 2, we first generate a set of f-FS SWs along the working route, where f is the number of FSs that the demand requires. Then we create an auxiliary graph AG_w for each SW w, as

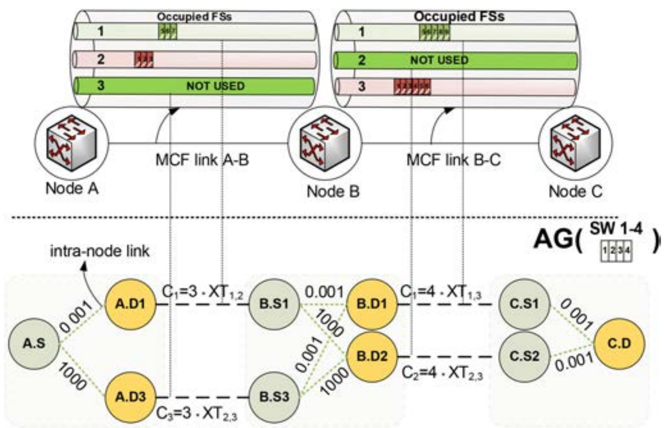


Fig. 5. Create an auxiliary graph for an SW.

illustrated in Fig. 5, where we assume that the working route is A-B-C and each link has three cores. As shown in the figure, at the time this demand is considered, part of spectrum in some cores is occupied by previously established lightpaths; for instance, cores 1&2 in link A-B and cores 1&3 in link B-C. On the other hand, core 3 in link A-B and core 2 in link B-C do not carry any lightpaths. Let us assume that the demand requires $f = 4$ FSs, and consider the SW with FSs 1-4. The resulting AG is shown at the bottom of Fig. 5 and is constructed as follows.

First, each physical node X along the working route is split into two groups of auxiliary nodes, one node in each group corresponding to a core in an MCF for which the FSs in this window are all available. The left group of auxiliary nodes of X (denoted by the light green color in the figure) are labeled X.S1-X.Sc , while the right group of auxiliary nodes (denoted by the yellow color in the figure) are labeled X.D1-X.D c , where c is the number of cores. As special cases, the source node is only split into a single left node (i.e., Node A.S in the figure) and a right group of auxiliary nodes, and the destination node is only split into a left group of auxiliary nodes and a single right node (i.e., Node C.D in the figure). For cores with unavailable SWs, we do not create corresponding auxiliary nodes. For example, there are no auxiliary nodes A.D2, B.S2, B.D3, or C.S3 in the figure because in core 2 of link A-B and core 3 of link B-C some of FSs 1-4 of this window are already occupied.

Next, we create auxiliary links between the nodes of the AG that represent cores for which the FSs of the SW are available. For example, in Fig. 5, since the SWs in cores 1&3 along link A-B are available, we create corresponding auxiliary links A.D1-B.S1 and A.D3-B.S3; these links indicate that the given demand may be carried along link A-B on a lightpath that uses either core 1 or core 2. Similarly, we create links B.D1-C.S1 and B.D2-C.S2 since the SW is available on cores 1&2 along link B-C. The cost of each such auxiliary link is set as the total inter-core crosstalk of the SW in its corresponding core. For example, since FSs 1-3 in core 2 of link A-B are occupied by previous lightpaths, we set the cost of cores 1&3 as $C_1 = 3 \cdot XT_{12}$ and $C_3 = 3 \cdot XT_{23}$, respectively (the factor 3 in these costs is due to the fact that this window and the occupied spectrum in core 2 are overlapped by 3 FSs). Similarly, since FSs 1-6 in core 3 of

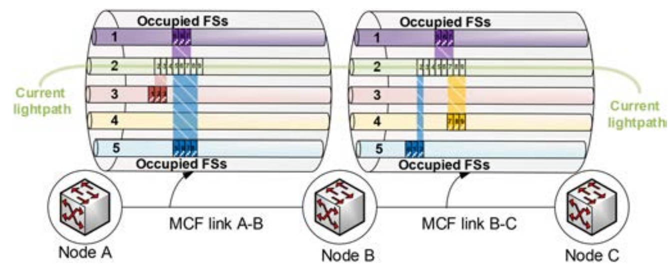


Fig. 6. Inter-core crosstalk of a lightpath in 5-core MCF network.

link B-C are occupied other lightpaths, we set the cost of cores 1&2 as $C_1 = 4 \cdot XT_{13}$ and $C_2 = 4 \cdot XT_{23}$, respectively. We also note that, $XT_{13} < XT_{23}$ in the above expressions because the core pitch between cores 1 and 3 is larger than that between cores 2 and 3.

Finally, we create auxiliary links to connect the left and right groups of auxiliary nodes corresponding to a certain physical network node. Specifically, we create an auxiliary link connecting each node of the left group to each node of the right group. We refer to these auxiliary links as intra-node links since they represent lightpath switching from one core of the incoming link to another core of the outgoing link that takes place within a physical node. The cost of each intra-node link is set as follows. If its destination virtual node corresponds to an unused fiber core (e.g., from B-S3 to B-D2 where core 2 is not used), then its cost is set to be large, e.g., 1000; this is to avoid assigning spectrum in unused cores if spectrum resources are available in already used cores. Otherwise, the cost of the intra-node link is set to be small. For example, the cost of intra-link B.S1-B.D1 is set to be 0.001.

In Step 3, we apply the DFS algorithm on auxiliary graph AG_w to determine the set of paths between the source and destination nodes (i.e., A.S and C.D) in Fig. 5. If there is no feasible path between the source and destination nodes, then the current SW *w* cannot be used to provision the current lightpath; in this case, we continue with the next SW. Otherwise, if one or more paths exist, we first sort them in ascending order of cost and examine them to check if it can meet the "strictly constrained" inter-core crosstalk threshold. Specifically, we check each FS f of the SW to determine whether its accumulated crosstalk XT_f does not exceed a predefined inter-core crosstalk threshold. Here XT_f is expressed as

$$XT_f = \sum_{c \in \boldsymbol{C}, l \in \boldsymbol{L}} XT^l_{i,j} \cdot \sigma^{f,l}_{i,j} \tag{35}$$

where $\boldsymbol{L}$ is the set of links traversed by the lightpath, $XT^l_{i,j}$ is the inter-core crosstalk between cores i and j in link l , and $\sigma^{f,l}_{i,j}$ is a binary value that denotes whether FS f is occupied on both cores i and j on link l. Referring to Fig. 6, for a lightpath between node A and node C which uses FSs 2-9 in core 2, we calculate XT_f for each FS to check if it meets the inter-core crosstalk threshold. For instance, the accumulated crosstalk for FS 2 is calculated as $XT_2 = XT^{A-B}_{23} + XT^{B-C}_{25}$ since core 3 on link A-B and core 5 on link B-C both use FS 2. Similarly, $XT_4 = 0$ since FS 4 is not used in any core along the route.

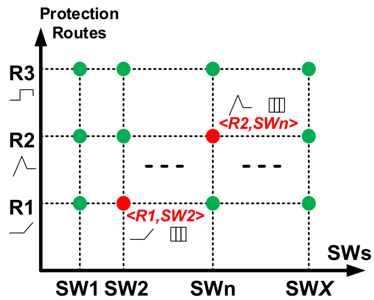


Fig. 7. Matrix of routes and SWs.

As one more example, $XT_7 = XT_{12}^{A-B} + XT_{25}^{A-B} + XT_{24}^{B-C}$ since two cores on link A-B and one core on link B-C use FS 7. If the crosstalk XT_f for any FS *f* of the SW is larger than the inter-core crosstalk threshold, this lightpath demand cannot be provisioned on this SW.

Under the "strictly constrained" inter-core crosstalk mode, we also need to calculate the new XT_f for all the previously established lightpaths for each FS that overlaps with the current lightpath since the establishment of the current lightpath might also increase the inter-core crosstalk of these existing lightpaths. If there are no new XT_f values exceeding the threshold, then we establish the current lightpath; otherwise, we continue with the next SW for the current lightpath demand. If no SW can be used for establishing the current working lightpath, we block this lightpath request.

If the working lightpath is established successfully, we then proceed to establish a protection lightpath for the current lightpath demand. In Step 4, we create a set of available SWs for each protection route in the route set $\boldsymbol{R}$ found in Step 1, following a process similar to the one we used for the working route. In this process, we follow the spare capacity sharing principle of the SBPP strategy to check if an FS is available. Clearly, if an FS is not occupied by any previously established working or protection lightpath then it is available. However, if an FS is occupied, we check the lightpath occupying it. If the FS is occupied by a working lightpath, it is unavailable. But if it is occupied by a protection lightpath, then we further check its corresponding working lightpath. If the latter shares a common link with the current working lightpath, then the FS is unavailable. Otherwise, we consider this occupied FS as available for spare capacity sharing. After finding all the available SWs in this manner, we generate a matrix as shown in Fig. 7 where the *y*-axis is the list of routes and the *x*-axis is the list of SWs on each of the routes. Each element in the matrix represents a combination $\langle R_i, SW_j \rangle$.

In Step 5, we construct an AG_P for each $\langle R_i, SW_j \rangle$ in the matrix of Fig. 7 using a process similar to the one illustrated in Fig. 5 for constructing the working AG_W.

In Step 6, we run the algorithm DFS on auxiliary graph AG_P to determine the set of candidate paths between the source and destination nodes. If there is no feasible path, then the current $\langle R_i, SW_j \rangle$ cannot be used to establish the current protection lightpath; therefore, we continue with the next one; otherwise, if one or more paths are available, we first sort them in ascending order of cost and examine them one by one to determine whether the crosstalk of a newly established lightpath and those of existing lightpaths can meet the inter-core crosstalk threshold. If no such path meets the inter-core crosstalk threshold, we continue with the next $\langle R_i, SW_j \rangle$ until we either find a path or we exhaust all $\langle R_i, SW_j \rangle$ combinations without finding one; in the latter case, we block this lightpath request.

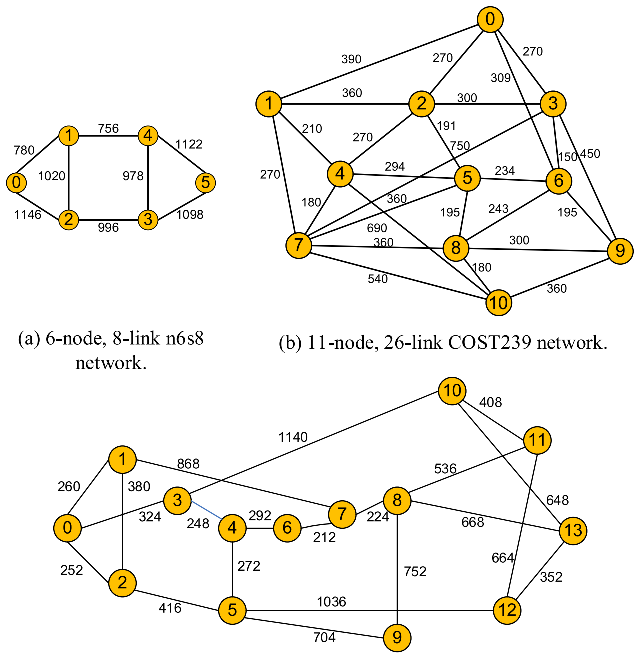
Note that multiple $\langle R_i, SW_j \rangle$ combinations may yield a feasible path for establishing a protection lightpath. Therefore, we consider two strategies to select a $\langle R_i, SW_j \rangle$ combination for the protection lightpath: first-fit (FF) and least cost (LC). The FF strategy terminates when a valid route is found, whereas the LC strategy examines all the eligible combinations and selects the one with the lowest cost.

C. Computational Complexity Analysis

In the above algorithm, the complexity of Dijkstra's algorithm and the DFS algorithm is $O(|\boldsymbol{N}|^2)$ and $O(|\boldsymbol{N}| \cdot (|\boldsymbol{N}| + |\boldsymbol{L}|))$, respectively, where $|\boldsymbol{N}|$ is number of network nodes and $|\boldsymbol{L}|$ is number of network links. In Step 2, we first generate sets of SWs, so its computational complexity is $O(W)$, where W is number of FSs carried. For each SW, we construct an AG; a step that takes time $O(|\boldsymbol{N}|^2 \cdot |\boldsymbol{C}| \cdot W)$, where $|\boldsymbol{C}|$ is number of cores in each MCF. In Step 4, we find a suitable SW and cores with the smallest inter-core crosstalk and also ensure the inter-core crosstalk of each lightpath to be less than a predefined threshold. We run the DFS algorithm to find eligible paths between a pair of auxiliary source and destination nodes. The complexity of this step $O(|\boldsymbol{N}| \cdot |\boldsymbol{C}| \cdot (|\boldsymbol{N}| \cdot |\boldsymbol{C}| + |\boldsymbol{L}| \cdot |\boldsymbol{C}|))$, where $|\boldsymbol{N}| \cdot |\boldsymbol{C}|$ is total number of nodes and $|\boldsymbol{L}| \cdot |\boldsymbol{C}|$ is total number of links in the AG topology, respectively. Therefore, the overall complexity of Step 4 is $O(W \cdot (|\boldsymbol{N}|^2 \cdot |\boldsymbol{C}|^2 + |\boldsymbol{N}| \cdot |\boldsymbol{C}|^2 \cdot |\boldsymbol{L}|) \cdot \boldsymbol{\Theta})$, where $\boldsymbol{\Theta}$ is the complexity of checking whether all lightpaths can meet the inter-crosstalk threshold when one of the paths found on the AG is used to establish a new lightpath. In Step 5, we generate sets of SWs and protection routes and form a matrix for $\langle R_i, SW_j \rangle$ combinations. This step takes time $O(W \cdot R)$, where R is the total number of protection routes. In Step 6, for each $\langle R_i, SW_j \rangle$ combination, we construct an AG; this step takes time $O(|\boldsymbol{N}|^2 \cdot |\boldsymbol{C}| \cdot W \cdot R)$. In Step 7, we find a $\langle R_i, SW_j \rangle$ combination with the smallest inter-core crosstalk and also ensure the inter-core crosstalk of each lightpath to be less than a predefined threshold. Therefore, the overall computational complexity is $O(W \cdot R \cdot (|\boldsymbol{N}|^2 \cdot |\boldsymbol{C}|^2 + |\boldsymbol{N}| \cdot |\boldsymbol{C}|^2 \cdot |\boldsymbol{L}|) \cdot \boldsymbol{\Theta})$.

VI. Performance Analyses

To evaluate the efficiency of the proposed CA-RCSA approach for SBPP lightpath services, we run simulations on the three test networks shown in Fig. 8: (1) a six-node, eight-link (n6s8) network, (2) the 11-node, 26-link COST239 network, and (3) the 14-node, 21-link NSFNET network. The distance of each link (in km) is shown next to the link. Both 7-core and 19-core MCFs are considered in the simulations, as shown in Fig. 9. The routes between node pairs used for the ILP model were obtained by Dijkstra's and DFS algorithms. We employed the commercial AMPL/Gurobi software package (version 5.6.2) [6] to solve the ILP model, which was run on a 64-bit machine with 2.4-GHz



(a) 6-node, 8-link n6s8 network.

(b) 11-node, 26-link COST239 network.

(c) 14-node, 21-link NSFNET network.

Fig. 8. Test networks.

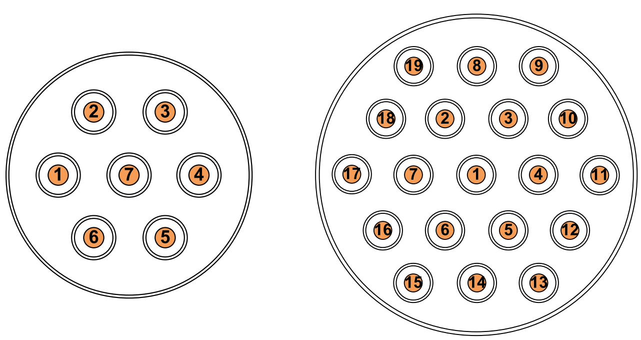


Fig. 9. Test MCFs.

TABLE III
MCF PARAMETERS USED FOR CALCULATING INTER-CORE CROSSTALK [18]

Parameters	Values
Δ	0.35%
cr	3.8 μm
V	2.2
U	$\sqrt{V^2 - W^2}$
W	$1.1428 \cdot V - 0.996$
br	10 cm
β	$4 \times 10^6\ m^{-1}$

CPU and 24-GB memory. The MIPGAP for solving the ILP model was set to 0.01%. The parameters used for estimating inter-core crosstalk in an MCF are given in Table III. The inter-core crosstalk threshold for a lightpath to be established was set to -30 dB [31]. For simplicity, in this study we set the same inter-core crosstalk threshold for all the lightpaths. However, it is possible to set different thresholds for different lightpaths according to their adopted modulation formats.

We run the ILP model on the small n6s8 network with 7-core MCFs, each core carrying 20 FSs, and a total of 20 requests. There is one pair of working and protection lightpaths for each request. The bandwidth of each demand is spectrally elastic, and it is distributed uniformly and randomly within the range [2, 2*X*-2] FSs, where *X* is the average number of FSs needed for a lightpath demand. Note that the number of FSs assigned to each lightpath is derived from the actual capacity demand between the corresponding node pair and the modulation format adopted according to the physical distance of the lightpath.

Because of the large sizes, we only ran the heuristic algorithm to evaluate the performance of the proposed approach on the COST239 and NSFNET networks. Each MCF is assumed to have 7 or 19 cores with each core carrying 320 FSs. A total of 500 lightpath demands were considered. In addition, since the order of lightpath demands provisioned may significantly affect the efficiency of the proposed approach, we shuffled the lightpath demand list 1000 times, and used the proposed CA-RCSA algorithm to provision lightpath services in each of the permutations. Eventually, we selected as the final solution the result of the permutation that achieved the best performance.

A. Number of Cores Used and Average Inter-Core Crosstalk

In this section, we compare the performance of the different schemes in terms of the number of cores used and the average inter-core crosstalk per FS of each lightpath, calculated as $\overline{CF} = \sum_{l\in \boldsymbol{L},i,j\in \boldsymbol{C},k\in \mathrm{W},i\neq j} A_{k,l}^{i,j}\cdot \Lambda_{i,j}^{l} \,/ \sum_{r\in \boldsymbol{NR}}(d_r + d'_{r,p})$, where $\boldsymbol{L}$ is the set of network links, $\boldsymbol{C}$ is the set of fiber cores, $\boldsymbol{NR}$ is the set of lightpath demands established, W is the number of FSs in each fiber core, and d_r and $d'_{r,p}$ represent the number of working FSs and protection FSs required when the lightpath demand *d* is provisioned using protection path p, respectively. The term $\sum_{l\in \boldsymbol{L},i,j\in \boldsymbol{C},k\in \mathrm{W},i\neq j} A_{k,l}^{i,j}\cdot \Lambda_{i,j}^{l}$ represents the total inter-core crosstalk in the whole network, and therefore, $\overline{CF}$ stands for the average inter-core crosstalk per FS of each lightpath. It should be noted that, although the metric for performance comparison is the average XT of all the lightpaths, each lightpath established is required to meet the predefined crosstalk threshold, i.e., -30 dB.

Fig. 10 compares the total number of cores used and the average inter-core crosstalk $\overline{CF}$ in the 7-core n6s8 network. Four schemes are compared, including the "ILP" model solved to optimality, the "SBPP" and "DPP" strategies for protection purposes, and the "Baseline" scheme. Here the "Baseline" scheme searches routes for lightpath establishment without checking inter-core crosstalk, i.e., non-crosstalk aware. We specifically consider this scheme for evaluating the benefit of crosstalk-awareness in the proposed CA-RCSA approach. As expected, all the schemes tend to use more cores with increasing bandwidth demands. In addition, because the baseline scheme does not consider the potential inter-core crosstalk when selecting routes for lightpath establishment, it ends up blocking one lightpath demand when the average demand $X = 8$, while all the other schemes can provision all the lightpath demands successfully. Moreover, we also observe that all the CA-RCSA strategies are

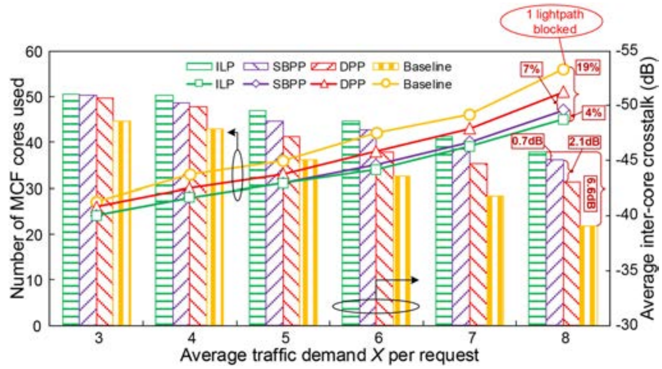
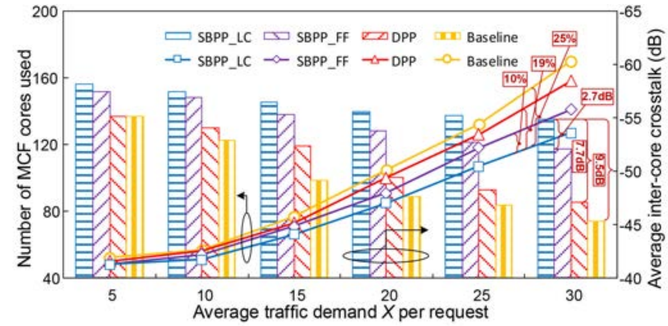


Fig. 10. Performance comparison in terms of the number of cores used and average inter-core crosstalk (n6s8, 7 cores).

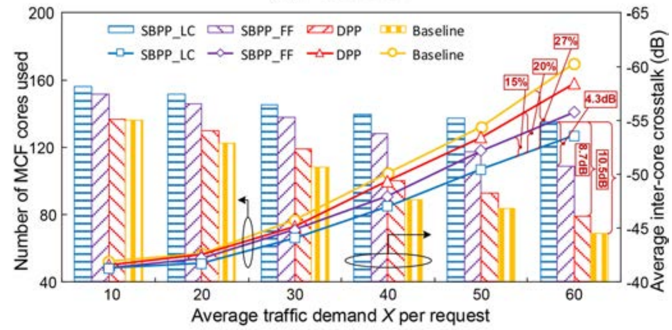
more efficient than the baseline crosstalk-unaware scheme, significantly reducing the number of cores required by up to 19%. In addition, comparing the two protection techniques, i.e., SBPP and DPP, the former also outperforms the latter by up to 7% in the number of fiber cores used. This is because SBPP allows spectrum resource sharing between protection lightpaths, while DPP needs to reserve dedicated protection spectrum resources. Finally, the performance of the SBPP strategy is very close to that of the ILP model. This further confirms the efficiency of the proposed heuristic algorithm for SBPP-based lightpath service provisioning.

We also evaluate the performance of the four schemes in terms of average inter-core crosstalk. The crosstalk-aware schemes significantly reduce the inter-core crosstalk, by up to 6.6 dB compared to the baseline algorithm. In addition, for the two protection techniques, SBPP outperforms DPP by up to 2.1 dB. Note that in Fig. 10, the right-hand y-axis is in a negative scale, which means that a taller bar corresponds to a smaller crosstalk. Finally, the performance of SBPP is close to that of the ILP model, confirming the effectiveness of the proposed heuristic algorithm in reducing inter-core crosstalk when provisioning SBPP-based lightpath services.

Fig. 11 shows a similar performance comparison for the larger COST239 network, which is too large to run the ILP model and hence we do not provide corresponding results. The legends "FF" and "LC" correspond to the FF and LC strategies for selecting $\langle R_i, SW_j\rangle$ combinations in the AG-based algorithm. We observe that, compared with the baseline algorithm, the proposed crosstalk-aware schemes again reduce the number of cores used by up to 25% and 27% for the 7-core and 19-core MCFs, respectively. As before, SBPP outperforms DPP by up to 19% and 20% for the 7-core and 19-core MCFs, respectively. We also observe that the LC strategy which considers all $\langle R_i, SW_j\rangle$ combinations and selects the lowest cost one performs better than the FF strategy that selects the first feasible combination that it finds: LC uses up to 10% and 15% fewer cores than FF used for the 7-core and 19-core MCFs, respectively. With respect to the inter-core crosstalk, the proposed crosstalk-aware schemes reduce the crosstalk by 9.5 dB and 10.5 dB for the 7-core and 19-core MCFs, respectively, relative to the baseline algorithm.



(a) 7-core MCF



(b) 19-core MCF

Fig. 11. Performance comparison in terms of the number of cores used and average inter-core crosstalk (COST239).

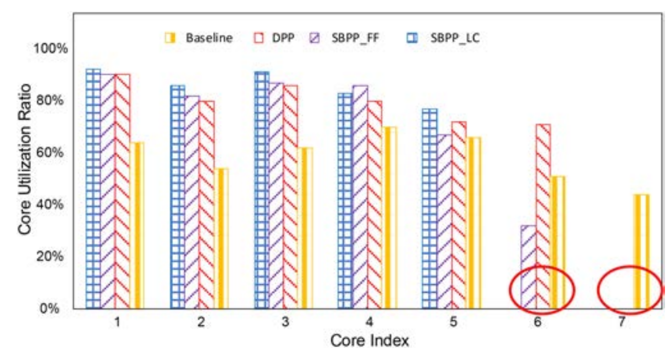


Fig. 12. Core utilization (7-core MCF NSFNET).

Again, SBPP performs better than DPP by up to 7.7 dB and 8.7 dB for the 7-core and 19-core MCFs, respectively. Similarly, the LC strategy reduces crosstalk relative to FF by 2.7 dB and 4.3 dB, respectively, for 7-core and 19-core MCFs.

In addition, we note that the performance improvement is more significant for the 19-core network than for the 7-core network. This is because 19-core MCF has a higher chance of finding a core with low inter-core crosstalk compared to a 7-core MCF.

B. *Impact of Layout on Core Utilization*

Let us now compare how core layout affects the relative utilization of cores in the 7-core and 19-core MCF networks. The layout of a 7-core MCF is shown in Fig. 9(a). Fig. 12 shows the core utilization on link N5-N9 of the NSFNET network with

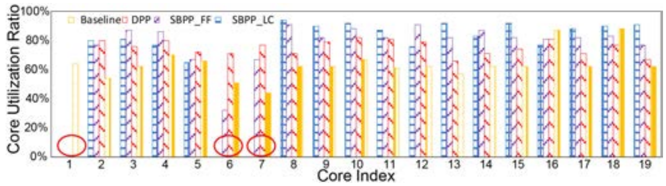


Fig. 13. Core utilization (19-core MCF NSFNET).

a 7-core MCF and traffic demands in the range of [5, 30] FSs. For the crosstalk-aware schemes, we see that the utilization of the outside cores (cores 1-6) is higher than the center core, i.e., core 7. This is because the center core suffers more inter-core crosstalk, so there is a lower chance of being selected by the crosstalk-aware scheme when provisioning a lightpath service. In contrast, utilization is relatively even across cores under the "baseline" scheme since it selects cores provisioning lightpath services without taking crosstalk in consideration.

In addition, we observe that the "SBPP_LC" scheme does not use core 6, whereas both "SBPP_FF" and "DPP" schemes use it. This is due to the fact that, in addition to avoiding inter-core crosstalk, the "SBPP_LC" scheme also tries to minimize the number of fiber cores used by exhaustively checking all possible cores.

Fig. 13 shows a similar performance comparison for the NSFNET with 19-core links and lightpath bandwidth demands in the range of [5, 60] FSs. We can also note that the crosstalk-aware schemes do not use the central core, i.e., core 1 in Fig. 9 (b). Moreover, the "SBPP_LC" scheme has the most unused cores, i.e., in addition to core 1, it avoids cores 6&7 as well. In contrast, both the "SBPP_FF" and "DPP" schemes use cores 6&7, which again verifies the effectiveness of exhaustively checking all possible cores by the LC strategy.

VII. Conclusion

We addressed the problem of SBPP-based lightpath provisioning in an MCF-EON. For the first time, we formulated the related CA-RCSA problem as an ILP model subject to the "strictly constrained" crosstalk threshold for each provisioned lightpath. In addition, we also developed an efficient crosstalk-aware heuristic algorithm to assign spectrum and cores in each fiber link for lightpath services to minimize the total number of cores used and the inter-core crosstalk suffered by lightpaths. The heuristic algorithm uses a novel auxiliary graph that reflects both the status of spare capacity sharing and the inter-core crosstalk, and allows for an efficient search to find a feasible combination of route, core and spectrum for a lightpath.

Simulation results show that the proposed crosstalk-aware approach is effective in SBPP-based lightpath service provisioning and can significantly reduce the number of cores used and the average inter-core crosstalk compared to a baseline scheme that is crosstalk-unaware.

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Fengxian Tang received the master's degree from Soochow University, Suzhou, China, where she is currently working toward the Ph.D. degree with Optical Network Technology Research Center, the School of Electronic and Information Engineering. Her research interests include the area of optical networking.

Gangxiang Shen (Senior Member, IEEE) received the B.Eng. degree from Zhejiang University, Hangzhou, China, the M.Sc. degree from Nanyang Technological University, Singapore, and the Ph.D. degree from the University of Alberta, Edmonton, AB, Canada, in 2006. He is currently a Distinguished Professor with the School of Electronic and Information Engineering, Soochow University, Suzhou, China. Before he joined Soochow University, he was a Lead Engineer with Ciena, Linthicum, MD, USA. He was also an Australian ARC Postdoctoral Fellow at the University of Melbourne, Melbourne, VIC, Australia. He has authored or coauthored more than 200 peer-reviewed technical papers. His research interests include spectrum efficient optical networks, green optical networks, and integrated optical and wireless networks. He was the Lead Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS Special Issue on Next-Generation Spectrum-Efficient and Elastic Optical Transport Networks and the Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS Special Issue on Energy-Efficiency in Optical Networks. He was an Associate Editor for the IEEE/OSA JOURNAL OF OPTICAL COMMUNICATION AND NETWORKING, and is currently an Associate Editor for the IEEE NETWORKING LETTERS and an Editorial Board Member of the *Optical Switching and Networking and Photonic Network Communications*. He was a Secretary of the IEEE Fiber-Wireless Integration Sub-Technical Committee. He was the recipient of the Young Researcher New Star Scientist Award in the 2010 Scopus Young Researcher Award Scheme in China, the Izaak Walton Killam Memorial Award from the University of Alberta, and the Canadian NSERC Industrial Research and Development Fellowship. He was selected as a Highly Cited Chinese Researcher by Elsevier in 2014–2019. He was an elected IEEE ComSoc Distinguished Lecturer from 2018 to 2019. He is a Member of the IEEE ComSoc Strategic Planning Standing Committee since 2018. He is currently a Technical Program Committee Member of the OFC and the ECOC. He is an elected Fellow of OSA.

George N. Rouskas (Fellow, IEEE) received the B.S. degree from the National Technical University of Athens, Athens, Greece, and the M.S. and Ph.D. degrees from the Georgia Institute of Technology, Atlanta, GA, USA. He is currently an Alumni Distinguished Graduate Professor and the Director of Graduate Programs with the Department of Computer Science, North Carolina State University, Raleigh, NC, USA. His research contributions have been in the areas of network architectures, optical networks, network design and optimization, and performance evaluation. He is on the OFC Steering Committee and was the Chair of ONTC, the Chair of the IEEE ComSoc Distinguished Lecturer Selection Committee, and the Distinguished Lecturer for the IEEE ComSoc. He was the recipient of the NSF CAREER Award, the 2004 ALCOA Foundation Engineering Research Achievement Award, the 2003 NC State Alumni Outstanding Research Award, and was inducted in the NC State Academy of Outstanding Teachers in 2004. He is the Founding Editor-in-Chief of the IEEE NETWORKING LETTERS, and was also the Founding Editor-in-Chief of the *Elsevier Optical Switching and Networking Journal* from 2004 to 2018. He was the Chair or the Co-Chair of numerous conferences, including the IEEE MASS 2018, IEEE ICC 2017 ONS, IEEE ICNP 2014, IEEE GLOBECOM 2010 ONS, IEEE LANMAN 2004 and 2005, and IFIP Networking 2004.