Minimizing Inter-Core Crosstalk Jointly in Spatial, Frequency, and Time Domains for Scheduled Lightpath Demands in Multi-Core Fiber-based Elastic Optical Network

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Abstract—**Elastic optical networks (EON) technology in combination with space division multiplexing (SDM) is considered as having the potential to expand the transmission capacity of optical transport networks. However, inter-core crosstalk may cause serious signal impairment in a multi-core fiber (MCF) links. At the same time, scheduled lightpath demands, for which the expected setup and teardown times are known in advance, are considered as an important type of traffic demand for future networks. In this article, we develop approaches to schedule simultaneous lightpaths onto non-adjacent MCF cores so as to reduce inter-core crosstalk between these lightpaths. To this end, we first define a new metric to estimate the inter-core crosstalk jointly considering the spatial, frequency, and time domains. We then tackle the routing, spectrum, core, and time assignment (RSCTA) problem for the MCF-based EON by developing an integer linear programming (ILP) model, as well as an auxiliary graph (AG) based heuristic algorithm, which jointly optimize spectrum resource utilization and reduce the lightpath inter-core crosstalk. Simulation studies show the effectiveness of the proposed approach in terms of both performance aspects. In addition, the performance of the proposed heuristic algorithm is shown to be close to that of the ILP model in small networks.**

Index Terms—**Inter-core crosstalk, RSCTA, MCF-based EON, scheduled lightpath demand.**

I. INTRODUCTION

THE proliferation of bandwidth-intensive applications such as ultra-high definition video, data center, and mobile traffic has led to an explosive increase of Internet traffic. Meanwhile,

it is recognized that modern fiber-optic communication systems based on standard single mode fibers (SSMFs) have reached their transmission capacity limit [1]. To keep pace with the fast growth of Internet traffic, new technologies are required to upgrade the transmission capacity of optical transport networks. Elastic optical networks (EON) is one such potential technology due to its flexible network bandwidth allocation and efficient spectrum utilization [2]. At the same time, space division multiplexing (SDM) based optical transmission systems have attracted significant research attention recently as a technology to further increase the transmission capacity of an optical transport network. According to [3], there are several techniques eligible to enable the SDM transmission, including single-mode fiber bundle, multi-core fiber (MCF), multi-mode fiber (MMF)/few-mode fiber (FMF), hollow-core photonic band gap fiber (HC-PBGF), etc. While all these SDM techniques have their own pros and cons, this study specifically looks into the MCF scenario to consider the combination of EON and MCF, i.e., MCF-based EONs.

For an MCF-based EON, inter-core crosstalk is one of the most important challenges with MCF transmission, in that it may severely degrade the quality of optical signals transmitted in two neighboring fiber cores. To reduce inter-core crosstalk, extensive studies have been carried out to properly assign spectrum and fiber core resources when establishing lightpaths in an MCF optical network [4]. Nevertheless, many existing works on lightpath service provisioning have assumed static or dynamic lightpath demands [5], [6]. In practice, however, clients may request scheduled lightpath demands, whereby setup and teardown times are known in advance [7]. Scheduled lightpaths are often established to carry delay-tolerant services, such as data replication and grid computing [8]. Though there have been studies on provisioning scheduled lightpath demands in space division multiplexed EONs (SDM-EONs) [9], [10], we are not aware of any studies on jointly optimizing network capacity utilization and minimizing lightpath inter-core crosstalk in such networks. In this study, we focus on such a joint optimization.

The key contributions of this study are as follows. Specifically, we consider the routing, spectrum, core, and time assignment (RSCTA) problem in the context of scheduled lightpath service provisioning and make two key contributions. First, we develop

an efficient approach to establish scheduled lightpath demands in non-adjacent MCF cores so as to simultaneously minimize the spectrum resources used and reduce inter-core crosstalk in an MCF-based EON. We also define a new metric to estimate the inter-core crosstalk jointly incorporating the spatial, frequency, and time domains.

The present research significantly broadens and generalizes our preliminary study [11]. Specifically, we develop a novel ILP optimization model for the RSCTA problem, and significantly extend the RSCTA heuristic algorithm in [11]. The heuristic algorithm selects MCF cores for lightpath demand establishment in a crosstalk-aware manner based on the parameter previously defined to estimate the inter-core crosstalk. Simulation results show that the crosstalk-aware RSCTA approach is efficient in not only reducing inter-core crosstalk but also improving network capacity utilization. We also find that the proposed heuristic algorithm is efficient and performs close to the ILP model in both spectrum resource utilization and lightpath inter-core crosstalk.

The rest of this paper is organized as follows. In Section II, we review related work on inter-core crosstalk reduction in MCF networks and scheduled lightpath demand provisioning. In Section III, we introduce inter-core crosstalk in the spatial, frequency, and time domains. We present an ILP model and a heuristic algorithm for the RSCTA problem in Sections IV and V, respectively. We carry out a performance evaluation in Section VI and conclude the paper in Section VII.

II. RELATED WORK

A. Inter-Core Crosstalk in MCF Optical Networks

An SDM optical network with weakly coupled MCFs is prone to signal impairment because of inter-core crosstalk [3]. It is important to address this issue when planning and operating such a network. 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, i.e., *best-effort avoidance* and *best-effort core prioritization*.

Best-effort avoidance techniques attempt to minimize inter-core crosstalk between neighboring cores when establishing a new lightpath. In [12], Shi *et al.* proposed a routing, spectrum, and core assignment (RSCA) algorithm to support super-channels in flex-grid enabled SDM networks. In [13], Oliveira and Da Fonseca introduced a heuristic algorithm for lightpath establishment in SDM-EONs with shared path protection. In [14], Muhammad *et al.* formulated the programmable filterless network dimensioning problem in MCF-based SDM networks using an ILP model.

Best-effort core prioritization methods have a similar goal, but they additionally implement a dedicated core prioritization mechanism. When cores are assigned to a lightpath, they are analyzed in sequence for deciding their priorities. Specifically, the priority of each core is determined by the extent to which they may reduce the dominant inter-core crosstalk. The further inter-core crosstalk can be reduced, the higher the priority of a core. In [15], Fujii *et al.* proposed an on-demand spectrum and core allocation (SCA) algorithm to solve the spectrum fragmentation problem in SDM-EONs. In [16], Beyragh *et al.* introduced an intelligent fragmentation-aware, routing, spectrum, and core

allocation (IF-RSCA) approach based on multi-criteria decision making (MCDM) methods. In [17], Tode and Hirota considered the routing, spectrum, and core and/or mode assignment (RSCMA) problems for SDM-EONs. They solved the RSCMA problem by dividing it into routing and SCMA sub-problems that allow for fast and efficient resource allocation solutions.

Strictly constrained approaches estimate the inter-core crosstalk of each lightpath in advance, and establish it only if the inter-core crosstalk between this new lightpath and all existing lightpaths is below a predefined threshold. In [18], Rottondi *et al.* developed an ILP model for the RSA problem in a few-mode fiber SDM network to explore the tradeoff between spectrum utilization and the number of transceivers required. In [19], Klinkowski *et al.* evaluated the impact of the worst-case inter-core crosstalk in SDM-EONs under different modulation formats. In [20], Tang *et al.* considered assigning fiber cores in a counter-propagating manner when establishing lightpaths, thus reducing inter-core crosstalk. They developed an ILP model and a heuristic algorithm based on an auxiliary graph to optimize spectrum resource utilization and reduce inter-core crosstalk. In [21], Zhang *et al.* addressed the anycast routing, spectrum, and core allocation (ARSCA) problem in MCF-based EONs, they formulated the problem as an ILP model and proposed a heuristic algorithm to efficiently solve it. In [22], Yao *et al.* introduced a machine learning approach to predict inter-core crosstalk and proposed a crosstalk estimation model to evaluate the inter-core crosstalk when allocating spectrum resources to lightpaths. In [23], Yang *et al.* developed a node-arc ILP model that considers the inter-core crosstalk based on the worst-case scenario. They also proposed a heuristic algorithm that considers strictly inter-core crosstalk when establishing a lightpath. In [24], Zhao *et al.* considered the issue of super-channel provisioning in SDM-EONs, and they proposed a mixed super-channel oriented routing, spectrum, and core assignment (MS-RSCA) algorithm to strictly consider inter-core crosstalk when establishing a lightpath. In [25], Oliveira and Da Fonseca proposed an algorithm called spectrum overlap, traffic grooming and failure-independent path protecting p-cycle (STOP) for failure protection in SDM-EONs.

B. Scheduled Lightpath Demands

There are also extensive studies on provisioning either *fixed* or *sliding* scheduled lightpath demands. With fixed scheduled demands, the setup and teardown times are pre-determined and known in advance. For this type of demands, Kuri *et al.* developed a branch and bound algorithm and a tabu search approach to solve the routing and wavelength assignment (RWA) problem in a WDM network [26]. In [27], [28], Li and Wang formulated the joint RWA problem as an integer linear model to maximally reuse network resources in both space and time domains. In [29], Tornatore *et al.* exploited the knowledge of connection-holding time to design an efficient algorithm, called PHOTO, for dynamic lightpath service provisioning with the consideration of shared path protection in an optical mesh network.

Sliding scheduled lightpath demands are more general and allow a lightpath demand to *slide* within a specific window. That is, a demand may be scheduled at any time within the

window and the actual starting and ending times are determined by an appropriate resource allocation scheme. For this type of demands, Wang *et al.* proposed a heuristic algorithm to schedule demands and implement the RWA step in a fault-free WDM network [30]. In [31], Jaekel and Chen developed new ILP models for provisioning both fixed and sliding scheduled lightpath demands, and also proposed a two-step heuristic algorithm to fulfill lightpath provisioning; they further considered the same problem for a survivable optical network [32].

In further related work, Chen *et al.* [33] provisioned scheduled lightpath demands based on the notion of time-spectrum consecutiveness (TSC), which measures the spectrum fragmentations on the spectrum and time axes. In [34], Afsharlar *et al.* developed an efficient approach, called delay spectrum allocation (DSA), to allocate spectrum resources for scheduled unicast and anycast lightpath demands in an EON. In [35], Wang *et al.* developed an optimization algorithm that considered three re-provisioning policies for dynamically re-provisioning a set of scheduled lightpath demands. In [36], Wang *et al.* developed a routing, modulation, and spectrum assignment (RMSA) algorithm based on a two-dimensional resource model. The algorithm was able to reduce spectrum resource fragmentation and achieve high spectrum utilization for scheduled lightpath demands in an EON.

C. Our Contributions

Though there have been extensive studies on MCF optical networks and scheduled lightpath demand provisioning, little work has been done to reduce the inter-core crosstalk when provisioning scheduled lightpath demands in an MCF-based EON. To bridge this gap, in this study we jointly consider the aspects of lightpath routing, and spectrum, core, and time assignment when provisioning scheduled lightpaths. Moreover, we also minimize the inter-core crosstalk between lightpaths in neighboring MCF cores when establishing lightpaths. Specifically, we define a new metric to measure the inter-core crosstalk jointly in the spatial, frequency, and time domains. Based on this, we further develop an ILP optimization model and an efficient heuristic algorithm to provision scheduled lightpath demands. In this study we consider the more challenging *sliding* demands, for which there is higher flexibility in setting their starting time. Moreover, to guarantee the quality of signal of each provisioned lightpath, we require the inter-core crosstalk of each established lightpath to be *strictly* constrained, that is, the inter-core crosstalk suffered by each newly established lightpath and all existing lightpaths must not exceed a certain threshold.

III. Inter-Core Crosstalk

We introduce the inter-core crosstalk from the spatial, frequency, and time domains.

A. Spatial Domain

In the spatial domain, the inter-core crosstalk between different core pairs in an MCF depends strongly on the core pitch (i.e., the distance between a pair of cores) [20]. Fig. 1 shows the
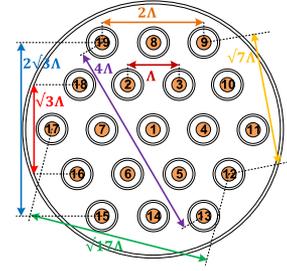

Fig. 1. A 19-core MCF with seven different types of core pitches.

example of a 19-core MCF, where seven different core pitches are demonstrated. Based on the core pitch, we can calculate the inter-core crosstalk $XT_{i,j}$ between cores i and j using Eq. (1), where $h_{i,j}$ is the power coupling coefficient and L is the fiber length. $h_{i,j}$ is the mean inter-core crosstalk increase per unit length along the fiber, which is mathematically expressed as Eq. (2). br and β are the bending radius and the propagation constant, respectively, whereas $k_{i,j}$ and $\Lambda_{i,j}$ are the coupling coefficient and the core pitch between cores i and j, respectively. According to optical waveguide theory, $k_{i,j}$ is calculated by Eq. (3), where Δ is the relative refractive index difference, Λ is the core pitch, cr is the core radius, U and W are the normalized transverse wave numbers in the core and cladding, respectively, and V is the normalized frequency. It should be noted that this is a generic analytical model to calculate the inter-core crosstalk for all types of core layouts, including hexagonal [23] and non-hexagonal [37]. Based on these equations, we can estimate the inter-core crosstalk between different core pairs.

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

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

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

B. Frequency Domain

Significant inter-core crosstalk occurs only between lightpaths in different cores that use the same spectrum. Therefore, in the frequency domain, we need to consider the amount of spectrum overlap between lightpaths. To this end, we define the FS-weighted inter-core crosstalk as

$$XT_{i,j}^{\mathbf{F}} = \sum_{f \in \mathbf{F}} XT_{i,j} \cdot \delta_{i,j}^f \tag{4}$$

Here, $\mathbf{F}$ is the set of frequency slots (FSs) considered and $\delta_{i,j}^f$ is a binary value that denotes whether FS f is used by lightpaths in both cores i and j. Fig. 2 shows an example of a 19-core MCF with lightpaths established in various cores. For clarity, we only show 5 cores in the figure, where different FSs are used in each core. Inter-core crosstalk only occurs between lightpaths with overlapping FSs, as shown in three cases. We can calculate the
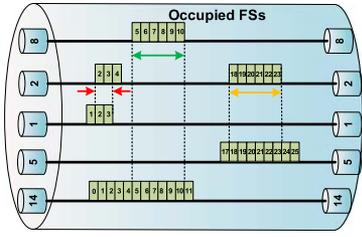
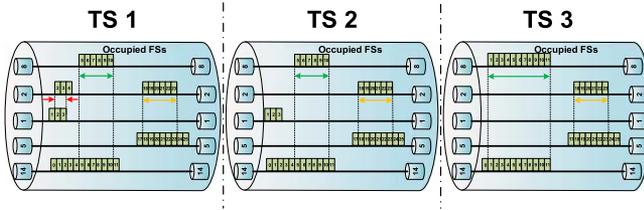Fig. 2.   A 19-core fiber with lightpaths established in the various cores.

Fig. 3.   A 19-core fiber with lightpaths established in TSs 1-3.

Fig. 4.   Architecture of amplification and switching systems in the MCF-SDM network.

inter-core crosstalk between any pair of cores using Eq. (4). For example, the inter-core crosstalk $XT_{1,2}^{F}$ between cores 1 and 2 is $XT_{1,2}^{F} = 2 \cdot XT_{1,2}$ since the two lightpaths in these cores have two FSs in common. Similarly, the overall inter-core crosstalk suffered by a specific core may be expressed as:

$$XT_i^{\boldsymbol{F}} = \sum_{f \in \boldsymbol{F}, j \in \boldsymbol{C}: j \neq i} XT_{i,j} \cdot \delta_{i,j}^{f} \qquad (5)$$

where $\boldsymbol{C}$ represents all the cores in this MCF. For example, the total inter-core crosstalk of core 2 in Fig. 2 is $XT_2^{F} = 2 \cdot XT_{1,2} + 6 \cdot XT_{2,5}$. Based on (5), we can find the inter-core crosstalk suffered by each core and optimally provision lightpath demands with a minimum total inter-core crosstalk for the whole network.

C. Time Domain

A scheduled lightpath demand is a lightpath service to be provisioned within a specific time window. We need to consider the time domain (represented by time slots (TS)) when provisioning the lightpath demand. In addition to spatially neighboring and overlapping in spectrum, inter-core crosstalk occurs between lightpaths only when they are simultaneously established. In general, a longer lightpath service duration would lead to more serious inter-core crosstalk. With the consideration of time domain, we further define the time-weighted inter-core crosstalk as Eq. (6), where $\boldsymbol{T}$ is the set of TSs considered and $\sigma_{i,j}^{f,t}$ is a binary value to denote whether FS f is used by lightpaths in cores i and j within TS t.

$$XT_{i,j}^{\boldsymbol{T},\boldsymbol{F}} = \sum_{f \in \boldsymbol{F}, t \in \boldsymbol{T}} XT_{i,j} \cdot \sigma_{i,j}^{f,t} \qquad (6)$$

Fig. 3 shows an example of FS usage in a 19-core MCF in TSs 1-3. For each core pair, we calculate the time-weighted inter-core crosstalk using Eq. (6). For instance, the total inter-core crosstalk between cores 8 and 14 is $XT_{8,14}^{\boldsymbol{T},\boldsymbol{F}} = 6 \cdot XT_{8,14} + 6 \cdot XT_{8,14} +$

$11 \cdot XT_{8,14}$, since lightpaths in the two cores overlap by 6 FSs in TSs 1 and 2, and by 11 FSs in TS 3.

Finally, we can calculate the inter-core crosstalk suffered by a lightpath in any core jointly considering the spatial, frequency and time domains as

$$XT_i^{\boldsymbol{T},\boldsymbol{F}} = \sum_{f \in \boldsymbol{F}, t \in \boldsymbol{T}, j \in \boldsymbol{C}: j \neq i} XT_{i,j} \cdot \sigma_{i,j}^{f,t} \qquad (7)$$

In Fig. 3, the inter-core crosstalk of core 2 is $XT_2^{T,F} = (2 \cdot XT_{1,2} + 6 \cdot XT_{2,5}) + (6 \cdot XT_{2,5}) + (6 \cdot XT_{2,5})$. Here, the three parts correspond to the inter-core crosstalk in the three TSs. In TS 1, there are two cores with spectrum overlapping that of core 2: core 1 with 2 FSs and core 5 with 6 FSs. In TSs 2 and 3, there are 6 FSs overlapping between cores 2 and 5.

After defining the inter-core crosstalk jointly in the spatial, frequency, and time domains, we can calculate the total inter-core crosstalk for each established lightpath. To ensure that lightpaths have good signal transmission qualities, each time a new lightpath is established, we need to make sure that the total inter-core crosstalk per FS per TS suffered on each of the links along the lightpath is no greater than a pre-defined threshold. If any link cannot guarantee this condition, then we do not allow this lightpath to be established on that path.

D. Amplification and Switching Inter-Core Crosstalk

In this study, we assume that the architecture demonstrated in [38] is employed for MCF signal amplification, whose functional architecture is equivalent to the one shown in Fig. 4(a) built from multiple independent single mode fiber EDFAs. Specifically, the fan-in/fan-out (FI/FO) component splits the MCF's cores into individual fibers, then each output of the FO is connected to an EDFA for amplification, and finally all the cores with amplified signals are aggregated onto a common MCF. With
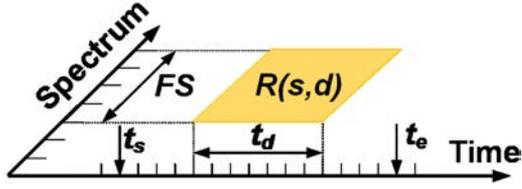
Fig. 5. A scheduled lightpath demand.

such an amplifier architecture, there will be no extra inter-core crosstalk generated. To efficiently utilize the pump lasers of optical amplifiers, more advanced architectures as in [39]–[41] that employ a single or few pump lasers can also be adopted so as to reduce the cost of this type of amplifier. In this case, we would need to consider the inter-core crosstalk in amplifiers.

For the switching system, we adopt an architecture similar to that of the amplification system. As shown in Fig. 4(b), we also use the FI/FO component to split and aggregate fiber cores and use an all-optical switching (i.e., OXC) module to switch signals in all fiber cores. As long as the switching component can well isolate signals from different cores, the inter-core crosstalk due to switching is also negligible.

IV. ROUTING, SPECTRUM, CORE, AND TIME ASSIGNMENT FOR SCHEDULED LIGHTPATH DEMANDS

For scheduled lightpath demands, we consider the routing, spectrum, core, and time assignment (RSCTA) problem for the MCF-based EON. In this section, we first define the RSCTA problem, and then develop an ILP formulation.

A. Problem Statement

The RSCTA problem for scheduled lightpath demands in an MCF-based EON can be formally stated as follows.

Given:
1) A general network topology represented by a graph $G(\mathbf{N}, \mathbf{L})$, where $\mathbf{N}$ is the set of nodes and $\mathbf{L}$ is the set of fiber links connecting nodes in $\mathbf{N}$;
2) A set of scheduled lightpath demands given *a priori*. As illustrated in Fig. 5, each demand is represented by a tuple $R(s, d, t_s, t_e, t_d, FS)$, where s and d are the source and destination nodes of the demand; t_s and t_e are the earliest service setup time and the latest service teardown time of the demand; t_d is the service duration of the demand, which should be between t_s and t_e; and FS is the number of FSs required. The shortest path between each node pair is always employed to carry these lightpath demands.

Constraints:
1) Demand serving constraint: All the lightpath demands must be served.
2) Core constraint: There is a limited number of cores in each MCF.
3) Core capacity constraint: There is a limited number of FSs in each core.
4) Time constraint: The duration t_d of each lightpath demand should be between the earliest service setup time t_s and the latest service teardown time t_e.

5) Spectrum contiguity: The set of FSs allocated to a lightpath must be spectrally contiguous.
6) Spectrum continuity: The set of contiguous FSs allocated in a core of an MCF must occupy the exact same part of the spectrum on each link traversed by the lightpath.
7) Crosstalk constraint: Each established lightpath should have an inter-core crosstalk no greater than a specific threshold.

Objective:
The RSCTA problem aims to establish lightpaths in an MCF-based EON so as to minimize both the total number of cores used and the inter-core crosstalk between lightpaths while satisfying all the above constraints.

B. ILP Model

We now present an ILP formulation for the RSCTA problem.

Sets:

$\mathbf{L}$	Set of network links.
$\mathbf{C}$	Set of cores in each MCF.
$\mathbf{NR}$	Set of node pairs in the MCF-based EON.
$\mathbf{P_r}$	Set of links along the shortest path between node pair $r \in \mathbf{NR}$. We assume that only the shortest path between each node pair may be used to carry lightpaths.
$\mathbf{Tw_r}$	Set of eligible time windows (TWs) for the lightpath demand between node pair $r \in \mathbf{NR}$.
$\mathbf{TS_r^w}$	Set of TSs in TW $w \in \mathbf{TW_r}$ for the lightpath demand between node pair $r \in \mathbf{NR}$.

Parameters:

d_r	Number of FSs required by demand r.
$\Lambda_{i,j}^l$	Inter-core crosstalk between cores i and j on link l.
W	Maximum number of FSs carried by each fiber core.
Ω	Maximum number of TSs considered in the whole process of scheduled lightpath service provisioning.
M	A large value.
α	A weight factor, used to balance the first and second objectives in the objective function.
Ξ	A predefined inter-core crosstalk threshold.

Variables:

S_r	An integer variable denoting the starting FS index of the lightpath (established) between node pair r.
E_r	An integer variable denoting the ending FS index of the lightpath (established) between node pair r.
ρ_{r1}^{r2}	A binary variable that equals 1 if the starting FS index of node pair $r2$ is larger than that of $r1$; 0, otherwise.
X_w^r	A binary variable that equals 1 if, for node pair r, TW w is selected for lightpath establishment; 0, otherwise.
$O_{r,t}^{l,i}$	A binary variable that equals 1 if core i of link l is selected for establishing a lightpath between node pair r in time slot t; 0, otherwise.
U_l^i	A binary variable that equals 1 if core i of link l is used; 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.

$\theta_{l,t}^{i,k}$ A binary variable that equals 1 if FS k in core i of link l is used in TS t; 0, otherwise.

$A_{l,t}^{i,j,k}$ A binary variable that equals 1 if cores i and j of link l both use FS k for lightpath establishment; 0, otherwise.

$y_r^{i,j,k,l,t}$ A binary variable that equals 1 if $A_{l,t}^{i,j,k} \cdot O_{r,t}^{l,i} = 1$; 0, otherwise.

Objective:

$$\text{Minimize} \sum_{l \in \boldsymbol{L}, i \in \boldsymbol{C}} U_l^i + \alpha$$

$$\cdot \sum_{l \in \boldsymbol{L}, i,j \in \boldsymbol{C}, 1 \leq t \leq \Omega, 1 \leq k \leq W, i \neq j} A_{l,t}^{i,j,k} \cdot \Lambda_{i,j}^l \qquad (8)$$

Our objective is to minimize the weighted sum of the total number of MCFs used plus the total inter-core crosstalk between lightpaths in the whole network.

Subject to:

−*TW selection constraint*

$$\sum_{w \in \boldsymbol{TW_r}} X_w^r = 1 \; \forall r \in \boldsymbol{NR} \qquad (9)$$

−*FS assignment constraints*

$$E_r - S_r - d_r + 1 = 0 \; \forall r \in \boldsymbol{NR} \qquad (10)$$

$$E_r \leq W \; \forall r \in \boldsymbol{NR} \qquad (11)$$

$$\rho_{r1}^{r2} + \rho_{r2}^{r1} = 1 \; \forall r1, r2 \in \boldsymbol{NR}, r1 \neq r2 \qquad (12)$$

$$E_{r2} - S_{r1} \leq M \cdot \left(\rho_{r1}^{r2} + 1 - O_{r1,t}^{l,i} + 1 - O_{r2,t}^{l,i} + 1 \right.$$
$$\left. - X_{w1}^{r1} + 1 - X_{w2}^{r2} \right) - 1 \; \forall r1, r2 \in \boldsymbol{NR}, i \in \boldsymbol{C}, w1 \in$$
$$\boldsymbol{TW_{r1}}, w2 \in \boldsymbol{TW_{r2}}, t \in \boldsymbol{TS_{r1,w1}} \cap \boldsymbol{TS_{r2,w2}}, l \in$$
$$\boldsymbol{P_{r1}} \cap \boldsymbol{P_{r2}}, r1 \neq r2 \qquad (13)$$

−*Fiber core assignment constraints*

$$\sum_{i \in \boldsymbol{C}} O_{r,t}^{l,i} - 1 \leq M \cdot (1 - X_w^r) \; \forall r \in \boldsymbol{NR}, w \in$$
$$\boldsymbol{TW_r}, t \in \boldsymbol{TS_{r,w}}, l \in \boldsymbol{P_r} \qquad (14)$$

$$\sum_{i \in \boldsymbol{C}} O_{r,t}^{l,i} - 1 \geq -M \cdot (1 - X_w^r) \; \forall r \in \boldsymbol{NR}, w \in$$
$$\boldsymbol{TW_r}, t \in \boldsymbol{TS_{r,w}}, l \in \boldsymbol{P_r} \qquad (15)$$

$$U_l^i \geq O_{r,t}^{l,i} \; \forall r \in \boldsymbol{NR}, i \in \boldsymbol{C}, l \in \boldsymbol{P_r}, 1 \leq t \leq \Omega \qquad (16)$$

−*FS usage constraints*

$$k - S_r \leq M \cdot \beta_r^k \; \forall r \in \boldsymbol{NR}, 1 \leq k \leq W \qquad (17)$$

$$E_r - k \leq M \cdot \gamma_r^k \; \forall r \in \boldsymbol{NR}, 1 \leq k \leq W \qquad (18)$$

$$1 - \theta_{l,t}^{i,k} \leq M \cdot \left(3 - \beta_r^k - \gamma_r^k - O_{r,t}^{l,i} \right) \; \forall r \in \boldsymbol{NR}, l \in$$

$$\boldsymbol{P_r}, i \in \boldsymbol{C}, 1 \leq k \leq W, 1 \leq t \leq \Omega \qquad (19)$$

−*Inter-core crosstalk constraints*

$$1 - A_{l,t}^{i,j,k} \leq M \cdot \left(2 - \theta_{l,t}^{i,k} - \theta_{l,t}^{j,k} \right) \; \forall r \in \boldsymbol{NR}, l \in$$

$$\boldsymbol{P_r}, i,j \in \boldsymbol{C}, 1 \leq k \leq W, 1 \leq t \leq \Omega, i \neq j \qquad (20)$$

$$\sum_{i,j \in C, l \in \boldsymbol{P_r}: i \neq j} \Lambda_{i,j}^l \cdot y_r^{i,j,k,l,t} \leq \Xi \; \forall r \in \boldsymbol{NR}, l \in \boldsymbol{P_r}, 1$$

$$\leq k \leq W, 1 \leq t \leq \Omega \qquad (21)$$

$$y_r^{i,j,k,l,t} \leq A_{l,t}^{i,j,k} \; \forall r \in \boldsymbol{NR}, i,j \in C, l \in \boldsymbol{P_r}, l \in \boldsymbol{P_r}, 1$$

$$\leq k \leq W, 1 \leq t \leq \Omega : i \neq j \qquad (22)$$

$$y_r^{i,j,k,l,t} \leq O_{r,t}^{l,i} \; \forall r \in \boldsymbol{NR}, i,j \in C, l \in \boldsymbol{P_r}, l \in \boldsymbol{P_r}, 1$$

$$\leq k \leq W, 1 \leq t \leq \Omega : i \neq j \qquad (23)$$

$$y_r^{i,j,k,l,t} \geq A_{l,t}^{i,j,k} + O_{r,t}^{l,i} - 1 \; \forall r \in \boldsymbol{NR}, i,j \in \boldsymbol{C}, l \in$$

$$\boldsymbol{P_r}, l \in \boldsymbol{P_r}, 1 \leq k \leq W, 1 \leq t \leq \Omega : i \neq j \qquad (24)$$

Let us now discuss the various constraints of the formulation.

TW selection: Constraint (9) ensures that only one TW is selected for establishing the lightpath between a pair of nodes.

FS assignment: Constraint (10) ensures the relationship between the starting and ending FS indices. Constraint (11) ensures that the ending FS index of any lightpath must be no greater than the maximum number of FSs carried by each fiber core. Constraints (12) and (13) ensure the spectrum contiguity of a lightpath and they also ensure that the spectra of the lightpaths that share a common fiber core in any fiber link do not overlap.

Fiber core assignment: Constraints (14) and (15) ensure that if a lightpath is established in a TW, a fiber core should be selected in each fiber link along the route to carry the lightpath. Constraint (16) means that if a core in an MCF is used for establishing a lightpath, then this core is considered used.

FS usage: Constraints (17), (18), and (19) jointly check whether FS k is used in a fiber core of a fiber link.

Inter-core crosstalk: Constraint (20) checks whether an FS is used in two neighboring fiber cores. Specifically, $A_{t,l}^{i,j,k} = 1$ only when both of the neighboring cores use the FS. Based on this determination, the objective term $\sum_{l \in \boldsymbol{L}, 1 \leq t \leq F, i,j \in \boldsymbol{C}, 1 \leq k \leq W : i \neq j} A_{t,l}^{i,j,k} \cdot XT_{t,l}^{i,j}$ calculates the total amount of inter-core crosstalk in the whole network. Since the objective is trying to minimize the total inter-core crosstalk, the value $A_{t,l}^{i,j,k}$ would be 0 by default. Constraint (21) ensures that for each lightpath to be established, its inter-core crosstalk does not exceed a specific inter-core crosstalk threshold Ξ, in which $y_r^{i,j,k,l,t}$ is equivalent to the binary product $A_{l,t}^{i,j,k} \cdot O_{r,t}^{l,i}$. We also accommodate the nonlinear term $A_{l,t}^{i,j,k} \cdot O_{r,t}^{l,i}$ using the three linear constraints (22), (23), and (24), under which if $A_{t,l}^{i,j,k} = 1$ and $O_{r,t}^{l,i} = 1$, then $y_r^{i,j,k,l,t} = 1$.

V. HEURISTIC ALGORITHM FOR RSCTA PROBLEM

Since the RSCTA problem is NP-complete [42], we cannot expect to solve the ILP model to optimality within a reasonable
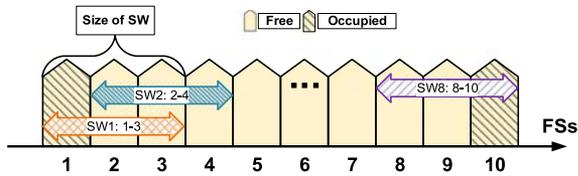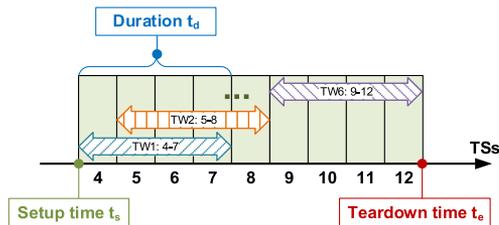
Fig. 6. Spectrum windows (SWs) in a fiber link.

Fig. 7. Example of time window (TW) for service duration.

Fig. 8. Combinations of TWs and SWs.

time even for medium-size networks. Therefore, in this section we develop an efficient heuristic algorithm to obtain near-optimal solutions in polynomial time. The algorithm applies the concepts of spectrum window (SW) [6] and time window (TW) to satisfy the contiguity and continuity constraints in allocating spectrum and time resources to lightpath demands.

A. Spectrum Window (SW)

The spectrum contiguity constraint requires that all FSs of a lightpath be spectrally neighboring. To enforce this constraint, we apply the concept of a spectrum window (SW) [6] which consists of a number of consecutive FSs equal to the demand size of a particular lightpath. Fig. 6 shows the SWs created for a 3-FS lightpath in a fiber link carrying a total of 10 FSs. Since the size of each window is 3, there are a total of 8 SWs. An SW is available only if all the FSs that it contains are free; otherwise, the SW is unavailable. In this example, SW 1 and SW 8 are unavailable.

The spectrum continuity constraint requires that the set of contiguous FSs allocated to a lightpath have the same indices on all fiber links traversed. Therefore, an SW is available along a route only if it is available on each MCF core that it traverses [43]. Only in this case do we consider the SW as a candidate for establishing the lightpath.

B. Time Window (TW)

A lightpath must be established for a contiguous time period equal to its service duration t_d, between the earliest service setup time t_s and the latest service teardown time t_e. Similar to an SW, a time window (TW) consists of a set of continuous TSs. Fig. 7 shows an example of TWs where the duration of each window is $t_d = 4$, with t_s and t_e equal to 4 and 12, respectively. As we can see, there are 6 TWs (i.e., TW1-TW6) between t_s and t_e, each consisting of 4 TSs. For example, TW1 occupies TSs 4-7 whereas TW6 occupies TSs 9-12.
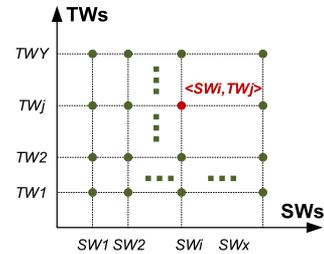
C. Crosstalk-Aware Spectrum, Core, and Time Assignment

We now propose an auxiliary graph (AG) based heuristic algorithm for the RSCTA problem. The key idea of this algorithm is to schedule lightpaths onto non-adjacent cores in the same time slots so as to reduce the inter-core crosstalk. Compared to conventional RSA algorithms that only have to consider the continuity and contiguity constraints in the spectrum domain, an additional challenge that arises is that an RSCTA algorithm must also consider the contiguity constraint in the time domain. Our approach is to exhaustively scan all possible combinations of SWs and TWs to select the one with the minimum inter-core crosstalk. The main steps of the algorithm are presented as follows.

Step 1: For a lightpath demand, use Dijkstra's algorithm to find a shortest route between the node pair of the demand.

Step 2: Create the sets of SWs and TWs for the current demand, along this shortest route.

Step 3: For each possible combination $\langle SW_i, TW_j \rangle$, create an auxiliary graph (AG) as we describe in detail shortly.

Step 4: Apply depth-first search (DFS) to determine all the routes, denoted as $\boldsymbol{P}$, between the source and destination nodes of the AG for the first combination of SW and TW. If there is no route between the source and destination nodes, continue with the next combination; otherwise, check all routes in $\boldsymbol{P}$ in ascending order of cost and select the first eligible route p that meets the inter-core crosstalk constraint. Assign the corresponding cores and spectra for the lightpath along route p.

In Step 1, we find the shortest route for the lightpath demand on the topology of the MCF-based EON.

In Step 2, for the current lightpath demand requiring f FSs, we generate a set of f-FS SWs along the shortest route. Similarly, for duration t_d, we generate a set of t_d-TS TWs between the earliest setup time t_s and the latest teardown time t_e of the lightpath demand. Based on these two sets of SWs and TWs, we generate a matrix as shown in Fig. 8 where the y-axis is the list of TWs and the x-axis is the list of SWs. Each element in the matrix represents a combination $\langle SW_i, TW_j \rangle$.

In Step 3, we create an AG for each $\langle SW_i, TW_j \rangle$ in the matrix of Fig. 9. The creation of the AG is illustrated in Fig. 9, where we
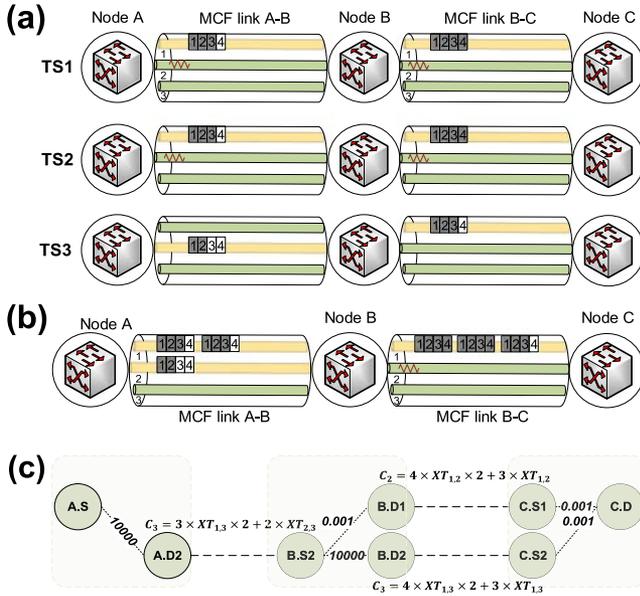
Fig. 9. Creating an auxiliary graph based on a combination of TW and SW.

Fig. 10. Estimating inter-core crosstalk for new and existing lightpaths.

assume a simple topology with just two 3-core MCF links; in this example, the TW contains TSs from 1 to 3 and the SW contains FSs from 1 to 4. Fig. 9(a) shows the spectrum usage of the various cores in TSs from 1 to 3. The yellow cores carry lightpaths in the current combination $\langle SW_i, TW_j \rangle$. The green cores marked with wave lines carry lightpaths, but these lightpaths do not belong to the combination $\langle SW_i, TW_j \rangle$. Finally, the green cores without wave lines do not carry any lightpaths. For example, in TS1, FSs 1-3 in core 1 are used on link A-B and FSs 1-4 in core 1 are used on link B-C. The cores with index 2 on both links A-B and B-C carry lightpaths in SWs different from FSs 1-4. Spectrum on the cores with index 3 on both links A-B and B-C has not been allocated yet, hence these cores do not carry any lightpaths. In TS2, FS allocations are identical to those in TS1. In TS3, FSs 1-2 in core 2 are used on link A-B and FSs 1-3 in core 1 are used on link B-C, while core 1 on link A-B is free and does not carry any lightpath.

Fig. 9(b) further summarizes the FS usage on each link in all the TSs. For example, on link A-B, FSs 1-3 in core 1 are used in TSs 1-2, FSs 1-2 in core 2 are used in TS 3, while core 3 is completely free; on link B-C, FSs 1-4 in core 1 are used in TSs 1-2, FSs 1-3 in TS 3, core 2 is used in other SWs, and core 3 is free.

Based on Fig. 9(b), we create an AG as shown in Fig. 9(c), where if a specific SW (i.e., FSs 1-4) of a core is not available in a specific TW (i.e., TSs 1-3), then no corresponding auxiliary link is set up. For example, core 1 and core 2 on link A-B and core 1 on link B-C are not available for this $\langle SW_i, TW_j \rangle$ combination. Therefore, an auxiliary link is set up only for core 3 on link A-B, and only for core 2 and core 3 on link B-C, as these are available for this $\langle SW_i, TW_j \rangle$ combination. We calculate the cost of the created auxiliary links as $XT_{i,j}^{T,F} = \sum_{f \in F, \, t \in T} XT_{i,j} \cdot \sigma_{i,j}^{f,t}$. For example, core 1 has lightpaths occupying FSs 1-3 in both TS 1 and TS 2, and core 2 has lightpaths occupying FSs 1-2 in TS 3.
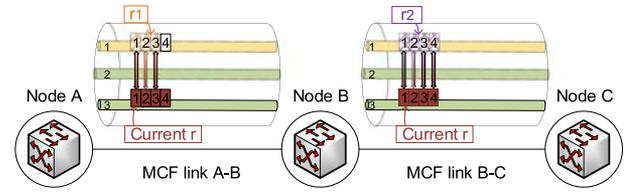
Therefore, we calculate the cost of the auxiliary link corresponding to core 3 on link A-B as $c3 = 3 \cdot XT_{1,3} \cdot 2 + 2 \cdot XT_{2,3}$. Similarly, we calculate the cost of the auxiliary links of core 2 and core 3 on link B-C as $c2 = 4 \cdot XT_{1,2} \cdot 2 + 3 \cdot XT_{1,2}$ and $c3 = 4 \cdot XT_{1,3} \cdot 2 + 3 \cdot XT_{1,3}$. Since the core pitch $\Lambda_{1,2} < \Lambda_{1,3}$, according to Eqs. (1), (2), and (3), the inter-core crosstalk $XT_{1,2} > XT_{1,3}$. Therefore, we can determine that the cost $c2 > c3$.

Next, to inter-connect MCF cores via a switch node, we add auxiliary links to fully connect the auxiliary nodes on both sides as shown in Fig. 9(c). The cost of each auxiliary link is set as follows. If its destination virtual node corresponds to an unused MCF core (e.g., from A.S to A.D2 where core 3 is not used), then its cost is set to be large, e.g., 10^4, to avoid using this unused core before using up spectrum resources on the other used cores. Otherwise, if the inter-connected auxiliary link corresponds to a used eligible core (e.g., B.S1-B.D1), then its cost is set to be small, e.g., 0.001.

In Step 4, based on the created AG, we first apply the depth-first search (DFS) algorithm to determine the set of paths between the source and destination nodes (i.e., A.S and C.D in Fig. 9). If there is no eligible path between the source and destination nodes, then the current $\langle SW_i, TW_j \rangle$ cannot be used to establish the current lightpath demand; in this case, we discard this $\langle SW_i, TW_j \rangle$ combination and continue with the next one. Otherwise, if one or more paths exist, we first sort them in ascending order of cost and examine them in that order in order to determine whether the crosstalk of a newly established lightpath and those of existing lightpaths that it influences meet the inter-core crosstalk threshold. In the above example, there are two eligible routes for the new lightpath: $A.S \rightarrow A.D2 \rightarrow B.S2 \rightarrow B.D1 \rightarrow C.S1 \rightarrow C.D$ and $A.S \rightarrow A.D2 \rightarrow B.S2 \rightarrow B.D2 \rightarrow C.S2 \rightarrow C.D$. We first examine the path $A.S \rightarrow A.D2 \rightarrow B.S2 \rightarrow B.D1 \rightarrow C.S1 \rightarrow C.D$ as illustrated in Fig. 10 for TS 1. There are 3 and 4 FSs already occupied by previously established lightpaths $r1$ and $r2$ on core 1 of link A-B and B-C, respectively. This route uses core 3 on both links along the route with the SW containing FSs from 1 to 4. We first calculate the crosstalk XT_f for each FS $f = 1, 2, 3$, and 4, of the new lightpath on this route. For example, $XT_1 = XTAB_{1,3} + XTBC_{1,3}$ since both lightpaths $r1$ and $r2$ occupy FS 1. If any XT_f is above the inter-core crosstalk threshold, we stop and discard this route. Otherwise, we proceed to calculate the new XT_f for all previously established lightpaths with FSs that overlap with the new lightpath (i.e., $r1$ and $r2$ in this example), and also check that they do not exceed the inter-core crosstalk threshold assuming

the new lightpath is established over this route. If no new XT_f values exceed the threshold, then we establish the new lightpath along this route and stop. Otherwise, we consider the next route, i.e., $A.S \rightarrow A.D2 \rightarrow B.S2 \rightarrow B.D2 \rightarrow C.S2 \rightarrow C.D$, and examine the inter-core crosstalk for all involved lightpaths again. If no routes meet the inter-core crosstalk threshold, then we continue to examine the next $\langle SW_i, TW_j \rangle$ combination and repeat all previous steps until either we find a valid route or we exhaust the $\langle SW_i, TW_j \rangle$ combinations. In the latter case, we block this lightpath request.

Note that in Step 4, there can be multiple eligible $\langle SW_i, TW_j \rangle$ combinations to establish a new lightpath. Therefore, we consider two strategies, first-fit (FF) and least cost (LC), to select a $\langle SW_i, TW_j \rangle$ combination for the new lightpath. The FF strategy stops examining combinations once a $\langle SW_i, TW_j \rangle$ combination when a valid route is determined; the LC strategy, on the other hand, examines all eligible combinations and selects the $\langle SW_i, TW_j \rangle$ combination and corresponding route that result in the lowest cost.

D. Computational Complexity Analysis

To determine the computational complexity of the heuristic algorithm, we note that the complexity of *Dijkstra's* algorithm is of the order $O(|N|^2)$, where $|N|$ is the number of network nodes. In Step 2, we generate sets of SWs and TWs and form a matrix for $\langle SW_i, TW_j \rangle$ combinations. The computational complexity of this step is of the order $O(W \cdot T)$, where W is the number of FSs carried in each fiber core and T is the total number of TSs between t_s and t_e. In Step 3, for each $\langle SW_i, TW_j \rangle$ combination, we construct an AG; this step takes time in the order of $O(|N|^2 \cdot |C| \cdot W \cdot T)$, where $|C|$ is the number of cores in each MCF. In Step 4, we find the SW_i, TW_j 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 of the order $O((W \cdot T \cdot |C|) \cdot \Theta)$, where Θ is the computational complexity of checking whether all the lightpaths can meet the inter-crosstalk threshold when one of the paths found on the AG is used to establish the new lightpath. We run the DFS algorithm to find eligible paths between the source node and destination nodes. The computational complexity of this step is $O(|N| \cdot |C| + |L| \cdot |C|)$, where $|N| \cdot |C|$ is the total number of nodes and $|L| \cdot |C|$ is the total number of links in the AG topology, respectively. Because we need to scan all $\langle SW_i, TW_j \rangle$ combinations in Step 3, the overall computational complexity of Step 4 is of the order $O(T \cdot W \cdot (\tau \cdot |N|^2 \cdot |C|^2 \cdot \Theta))$.

VI. PERFORMANCE ANALYSES

We evaluated the efficiency of the proposed crosstalk-aware RSCTA approaches by running simulations on three test networks: (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, as shown in Fig. 11. The distance of each link (in km) is shown next to the link. Both 7-core [20] and 19-core MCFs (see Fig. 1) are considered in the simulation study. The routes between node pairs used for the ILP model were
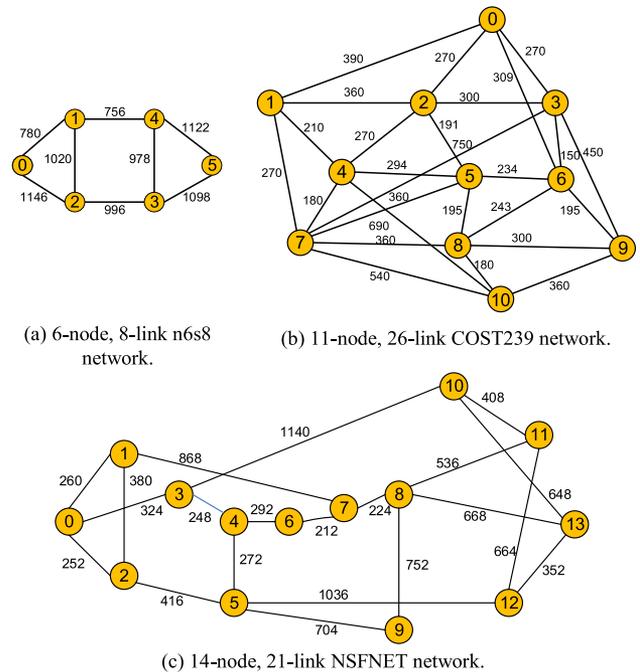

(a) 6-node, 8-link n6s8 network.

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

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

Fig. 11. Test networks.

TABLE I
MCF PARAMETERS USED FOR CALCULATING INTER-CORE CROSSTALK [20]

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

obtained by Dijkstra's algorithm. We employed the commercial AMPL/Gurobi software package (version 5.6.2) [6] to solve the ILP model, which was run on a 16-core 64-bit machine with 2.4-GHz CPU and 24-GB memory. The MIPGAP for solving the ILP model was set to be 0.01%. In the ILP model, the large value M is set to 100,000. In addition, since the first objective is the total number of MCF cores used which is within a range of [10, 50] while the second objective is the total inter-core crosstalk which is within a range of $[-50, 0]$ dB, we set $\alpha = 0.01$ to weight the first and second objectives. With such a configuration, we can guarantee that, if there are multiple solutions with the same value for the first objective, the one with the lowest total crosstalk (i.e., the best signal transmission performance) will then be selected. The parameters used for estimating inter-core crosstalk in an MCF are given in Table I. The inter-core crosstalk threshold for a lightpath to be established was set to be -30 dB [20].

For the ILP model, we considered the small n6s8 network with a total of 30 lightpath requests and 7-core MCFs, with each core carrying 20 FSs. The bandwidth of each scheduled

lightpath demand is spectrally elastic, and uniformly and randomly distributed within the range of [5], [20] FSs. The number of FSs assigned to each lightpath is derived from the actual capacity requirement between the corresponding node pair and the modulation format that is selected according to the distance or signal quality of the lightpath. The number of time slots considered in the whole simulation process is in the range of [0, 15]. The service duration t_d of each scheduled lightpath demand is randomly distributed within the range of [2, 2X-2] TSs, where X is the average lightpath service duration. Specifically, we first randomly generate the setup time t_s of each scheduled lightpath demand in the range of [0, 15], and then generate a larger number y using the duration t_d divided by a random value γ between [0, 1], i.e., $y = t_d/\gamma$. Then the ending service time of the scheduled lightpath demand is set to be $t_e = t_s+y$. Note that if $t_e > 15$, we discard the request and generate a new one to ensure that no lightpath service exceeds the maximum simulation time of 15 TSs. We repeat the above random process to generate a total of 30 scheduled lightpath demands.

Due to the size of the COST239 and NSFNET networks, we only ran the heuristic algorithm to evaluate the performance of the proposed approach. Each MCF is assumed to have 7 cores with each core carrying 320 FSs. A total of 500 scheduled lightpath demands were considered and the range of time slots in the simulation process was [0, 200]. Here we set the total number of time slots to be 200, and the relative time of each time slot can be adjusted according to the actual total time for service scheduling. For instance, if the total time for service scheduling is one year, then we can set each time slot to be 2 days, corresponding to more than one year in total time. In fact, given infrequent arrival and departure of lightpath services, a 2-day time slot is reasonable for lightpath services which normally exist in a backbone network. In addition, since the order of lightpath demands provisioned may dramatically affect the network resource utilization, we shuffled the scheduled lightpath demand list 1000 times, provisioned each of the permutations using the proposed crosstalk-aware RSCTA algorithm, and selected the permutation that resulted in the performance as our final solution.

We calculated the computation times of the different approaches. For the ILP model, it took more than 24 hours to obtain an optimal solution for the n6s8 network. For the heuristic algorithm, the computation time was less than 7 seconds for the n6s8 network and it was less than 1 minute for both COST239 and NSFNET networks.

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 channel, calculated as $\overline{CF} = \sum_{l\in \boldsymbol{L},i,j\in \boldsymbol{C},1\leq t\leq \Omega,1\leq k\leq W,i\neq j} A_{l,t}^{i,j,k} \cdot \Lambda_{i,j}^l / \sum_{d\in \boldsymbol{D}}(FS_d \cdot T_d)$, where $\boldsymbol{L}$ is the set of network links, $\boldsymbol{C}$ is the set of fiber cores, $\boldsymbol{D}$ is the set of scheduled lightpath demands established, Ω is the total number of TSs considered, W is the number of FSs in each fiber core, and FS_d and T_d represent the number of FSs required and the
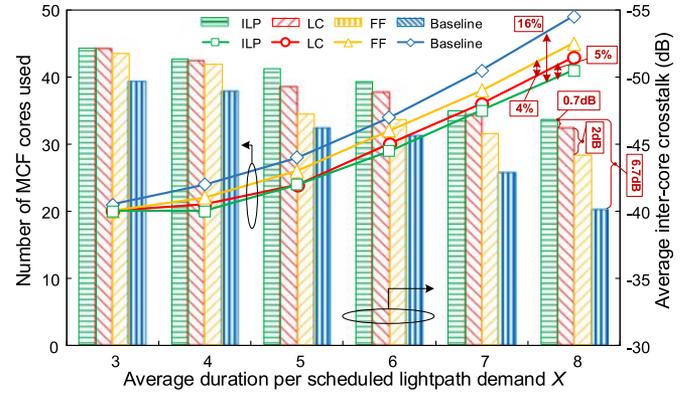

Fig. 12. Performance comparison in terms of the number of cores used and average inter-core crosstalk (n6s8, 7 cores).

service duration of lightpath demand d, respectively. The term $\sum_{l\in \boldsymbol{L},i,j\in \boldsymbol{C},1\leq t\leq \Omega,1\leq k\leq W,i\neq j} A_{l,t}^{i,j,k} \cdot \Lambda_{i,j}^l$ represents the total time-weighted inter-core crosstalk in the whole network, and therefore, $\overline{CF}$ stands for the average inter-core crosstalk per FS per TS of each lightpath. Although the performance metric for comparison purposes is the average XT of all the lightpaths established, each lightpath established was required to meet the predefined crosstalk threshold, i.e., -30 dB. In this case study, all the scheduled lightpath demands were established successfully.

Fig. 12 compares the total number of cores used and the average inter-core crosstalk $\overline{CF}$ for the 7-core network n6s8, as a function of service duration. Four strategies are compared in the figure: the "FF" and "LC" strategies for selecting $\langle SW_i, TW_j\rangle$ combinations in the AG-based algorithm, the "ILP" model solved to optimality, and a "Baseline" algorithm that establishes lightpaths without considering inter-core crosstalk.

We see that with as the service duration increases, all schemes tend to use more MCF cores. This is reasonable since (1) longer service duration requires more capacity to serve, and (2) lightpaths are active longer and hence have greater impact on other lightpaths in terms of crosstalk. Importantly, we observe that crosstalk-aware RSCTA strategies are effective compared to the baseline crosstalk-unaware algorithm, significantly reducing the number of cores used by up to 16%. Considering the LC and FF strategies, we see that the former outperforms the latter by up to 4% due to the fact that it exhaustively searches all $\langle SW_i, TW_j\rangle$ combinations and hence obtains better solutions. Moreover, the solutions obtained by the LC strategy are very close to those of the ILP model.

We make similar observations for the performance in terms of average inter-core crosstalk. Specifically, the crosstalk-aware RSCTA scheme significantly reduces the inter-core crosstalk, by up to 6.7 dB, compared to the baseline algorithm. Note that the y-axis on the right-hand side of Fig. 12 shows a negative average inter-core crosstalk in dB, so that a taller bar corresponds to a lower crosstalk. Also, the LC strategy achieves better performance than the FF strategy with up to 2-dB lower inter-core crosstalk. This is because the LC strategy scans all possible spectrum, core, and time assignment scenarios to find the one with the lowest crosstalk. Moreover, the LC strategy
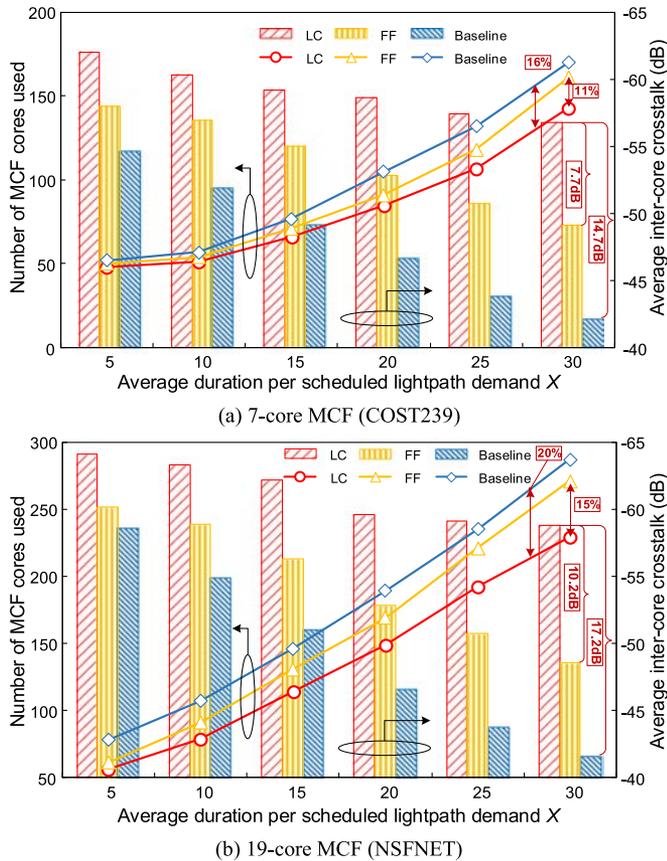
Fig. 13. Performance comparison in terms of the number of cores used and average inter-core crosstalk.

Fig. 14. Performance comparison in terms of the ratio of scheduled lightpaths established and average inter-core crosstalk

values are very close to that of the ILP model, confirming the effectiveness of the proposed heuristic algorithm in reducing inter-core crosstalk.

Fig. 13 shows similar performance comparisons for the two larger networks. However, because of the high computational complexity of the ILP model, in this case we only present results for the three heuristic algorithms, "LC," "FF," and "Baseline." Fig. 13(a) shows the results for the COST239 network (with 7-core fibers) and Fig. 13(b) shows the results of the NSFNET network (with 19-core fibers). We observe that, compared to the baseline algorithm, our crosstalk-aware algorithm significantly reduces the number of cores used by up to 16% and 20% for the COST239 and NSFNET network, respectively. Also, we find that the LC strategy again outperforms the FF strategy by up to 11% in terms of cores used for the 7-core COST239 network, and by up to 15% in the 19-core NSFNET network. With respect to inter-core crosstalk, our scheme reduces crosstalk by 14.7 dB (COST239) and 17.2 dB (NSFNET), compared to the baseline algorithm. Finally, the LC strategy outperforms the FF strategy by 7.7 dB and 10.2 dB, respectively, on the COST239 and NSFNET network. Morevoer, as a general obervation, the performance of the NSFNET is better than that of the COST239 network. This is due to the fact that the NSFNET network has 19 cores in each MCF, hence a demand has a higher chance of finding a core with lower inter-core crosstalk compared to a 7-core MCF.
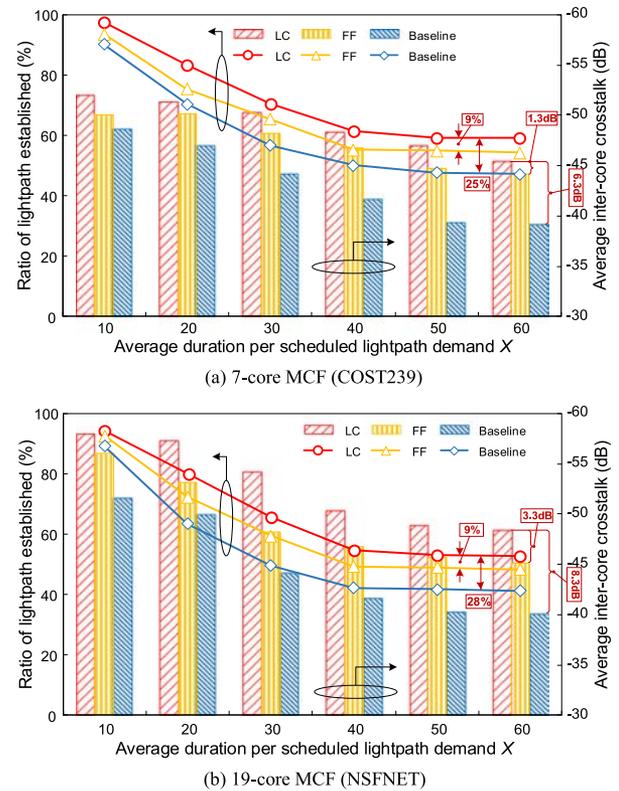
B. Successful Lightpath Establishment Ratio

In this section, we compare the ratio of successful established lightpaths under the different schemes with the same network resources. To this end, we increase the size of each scheduled lightpath demand so that it is now randomly distributed within the range of [20, 50] FSs. We also increase the duration of each scheduled lightpath demand. Under these assumptions, spectrum resources are limited and may not be sufficient to serve successfully all lightpath demands. Fig. 14 shows the ratio of successful established scheduled lightpath demands and the average inter-core crosstalk for the 7-core COST239 and the 19-core NSFNET. We see that with as service duration increases, all schemes show lower ratios. This is because an increasing duration occupies network resources for a longer time, and therefore, leaving fewer resources available for new lightpaths. It is also interesting to see that when the service duration reaches a certain number, the ratio of successful established lightpaths stays almost constant. This is because when the service duration of a scheduled lightpath demand is long enough, this demand is similar to a static lightpath demand, which requires almost fixed network resources. Comparing the crosstalk-aware RSCTA strategy and the baseline algorithm that ignores inter-core crosstalk, we can see that RSCTA yields a significantly higher ratio of successful established lightpaths, up to 25% and 28%, respectively, for the 7-core COST239 and the 19-core NSFNET networks. Also, the LC strategy outperforms the FF strategy by up to 9% under both networks. This is because

the LC strategy considers all possible spectrum, core, and time assignment scenarios to select the one with the lowest crosstalk.

Similar observations can be made for the inter-core crosstalk. We can see that the crosstalk-aware RSCTA scheme reduces inter-core crosstalk by up to 6.3 dB and 8.3 dB compared to the baseline strategy, respectively, for the 7-core COST239 and 19-core NSFNET networks. Also, the LC strategy achieves better performance than FF, with 1.3 dB and 3.3 dB lower inter-core crosstalk, respectively, for the COST239 and NSFNET networks. Again, we observe that the 19-core NSFNET network has better performance in terms of inter-core crosstalk than the 7-core COST239, since, with more cores, a demand has a higher chance of finding a core with lower inter-core.

VII. CONCLUSIONS

To minimize inter-core crosstalk for scheduled lightpath demands in a MCF-based EON, we proposed a novel crosstalk-aware routing, spectrum, core, and time (RSCTA) assignment scheme that jointly considers the spatial, frequency, and time domains when establishing a lightpath. An ILP model was developed for the assignment problem and an efficient heuristic algorithm called RSCTA was also proposed to assign spectrum and core resources in each fiber link at different time slots so as to minimize the number of cores used and the inter-core crosstalk. Simulation results show that the proposed strategy is effective in significantly reducing the number cores used as well as the average inter-core crosstalk, compared to a baseline algorithm that does not take inter-core crosstalk into consideration. Also, under the limited network capacity, the proposed strategy achieves a significantly higher successful ratio of establishing lightpaths compared to the baseline algorithm. Finally, the proposed RSCTA algorithm combined with the LC strategy is the most efficient and performs close to the ILP model for small networks.

Based on the current work, there are several interesting aspects to be further explored. First, besides the parallel independent EDFAs assumed in this study, it is also meaningful to consider the inter-core crosstalk of amplifiers when more advanced integrated MCF optical amplifiers are employed. Second, in addition to efficiently utilizing the network capacity, it is also necessary to consider the aspect of energy efficiency. The capacity density in current MCF-SDM networks can be quite high, hence, we also need to consider the energy consumption of key network components or devices such as transceivers, amplifiers, etc. Finally, the algorithm that we developed in this study is based on the assumption that the service duration and capacity requirement of each service request is known in advance. Thus, it would be useful to further extend the current algorithm to address online/continuous time network operation.

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