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Anycast Planning in Space Division Multiplexing Elastic Optical Networks with Multi-core Fibers

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***Abstract*—Elastic Optical Networks (*EONs*) play an important role for the next generation core networks, especially for supporting cloud computing. However, network traffic has been growing exponentially and almost reached the physical capacity limit of single mode fibers. Space division multiplexing (*SDM*) can be potentially employed to increase the fiber capacity. Multi-core fibers (*MCFs*) make use of SDM to aggregate multiple cores together into the cladding of one fiber, which can greatly increase the capacity of EONs but incurs new crosstalk constraints.**

Anycast is more flexible as compared to unicast, and anycast communications is widely used in cloud computing, distributed computing, distributed storage system, and content delivery networks. This paper formulates the anycast planning problem in the SDM EONs with MCFs. Evaluation results show that CVX and Gurobi tools can solve small size problems, but do not scale well. Therefore, we propose a heuristic algorithm to efficiently solve the problem. To our best knowledge, this is the first work that considers ancyast routing in the SDM EONs with MCFs.

***Index Terms*—Anycast, elastic optical network, routing and spectrum assignment, multi-core fiber, crosstalk.**

I. Introduction

Time division multiplexing (*TDM*) was studied before the 1980s; wavelength division multiplexing (*WDM*) was studied in the mid 1990s within the C and L bands; the digital coherent technology was studied in the late 2000s [1]. Today's exponential increase in Internet traffic is the driving force for augmenting the capacity of optical backbone networks. The transmission capacity has reached 100 Tb/s per fiber in the laboratory, and has achieved 10 Tb/s for commercialized systems. The transmission capacity will be 100 Tb/s over single mode fibers (*SMF*s) around the year 2020 [2, 3], which is the physical limit of SMFs. The physical capacity limit of SMFs is constrained by the nonlinear effect attribute and power transmission attribute of SMFs [4].

The space division multiplexing (*SDM*) technology is becoming the choice to overcome the capacity limit of the core networks in the future, and this technology can be implemented by multi-core fibers (*MCF*s). MCFs have many cores which are embedded in the cladding of the fibers, and the capacity of MCFs were demonstrated to nearly reach 1 Pb/s for each fiber; MCFs provide much higher capacity than SMFs [5, 6].

Much work has been done in SDM with MCFs. A static scenario with MCF networks was investigated in [7]; the authors employed the integer linear programming (*ILP*) to formulate the routing, spectrum and core allocation (*RSCA*) network planning problem for unicast requests, and a complicated crosstalk model was used with MCFs that increases the complexity of the *RSCA* problem. A dynamic scenario of unicast communications in SDM EONs with MCFs was shown in [8]. Advances in the SDM transmission field from the aspect of multi-core and multi-mode transmitting technologies have been summarized in [9]. Reference [10] provides the most recent research progress of SDMs in optical networks including multiplexers, transmitters, switches, and SDM nodes.

The spectrum utilization efficiency of elastic optical networks (*EONs*) is greatly improved by orthogonal frequency division multiplexing (*OFDM*) technique and EONs provide different modulation level formats according to the specific path condition, which can adaptively change the bandwidth of a concrete spectrum slot. The capacity of an EON is usually quite huge [11] and the EON provides quite small granularity with 12.5 GHz or less [12]. Routing and spectrum assignment (*RSA*) problem is a commonly studied problem in the EONs, and it is more complicated than the routing and wavelength assignment (*RWA*) problem in the WDM networks. In this paper, we study the anycast RSA problem but with MCFs, referred to as *a*nycast *r*outing, *s*pectrum and *c*ore *a*llocation (*ARSCA*) problem.

Anycast provisions flexible communications. A source node is known a *priori* for a given anycast request, and a set of destination nodes are given [13]. Anycast communications is widely used in cloud computing, distributed computing, distributed storage system, and content delivery networks; one user request may be provisioned cooperatively in many DCs or many servers through the network in cloud computing and content delivery networks [14]. Since anycast communications is widely used, it is important to study the anycast planning problem in SDM EONs overlaid on MCFs.

We formulate the ARSCA problem in SDM EONs overlaid on MCFs. To the best of our knowledge, this is the first work to address anycast communications in SDM EONs with MCFs. The rest of this paper is organized as follows: Section II formulates the ARSCA problem, Section III introduces the heuristic algorithm, Section IV presents the performance of the proposed algorithm along with its simulation results, and Section V concludes the paper.

II. MCF model and problem formulation

In this section, we employ a path-based ILP method to formulate the ARSCA problem.

A. Multi-core fiber model

A SDM EON with MCFs is shown in Fig. 1. Each link of this network is equipped with the same MCF, and each

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MCF has seven cores which are marked with different colors. Transmitting lightpath with the same frequency slots through the adjacent cores generate nonnegligible crosstalk to each other, such as core 1 and core 2; the crosstalk between nonadjacent cores is too low to measure, and we do not consider the crosstalk between nonadjacent cores; the center core which has more adjacent cores exhibits higher crosstalk, and then the lightpath transmission distance in this core is shorter than the other cores. We assume the same core is provisioned along a path for each lightpath request.

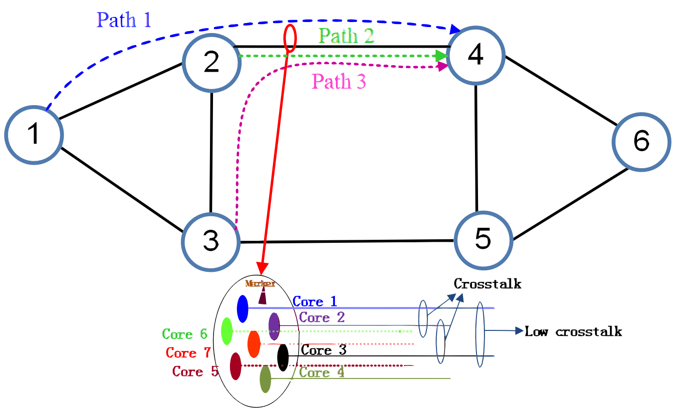

Fig. 1. An example of multi-core fiber networks.

Two different lightpath requests which share more than one link cannot be assigned with the same frequency slots (*FSs*) in traditional EONs. However, these two lightpath requests can be allocated with the same FS within different cores in the SDM EONs. In Fig. 1, path 1 is assigned with FSs in core 1, path 2 can be assigned with the same FSs in core 2 if the crosstalk does not reach the crosstalk threshold, and path 3 can be assigned with the same FSs in core 7 if the crosstalk does not reach the crosstalk threshold. Note that core 7 is the center core, and it can be used for a shorter distance transmission than the other cores.

Eq. (1) shows how to calculate the mean crosstalk of one core within a seven-core MCF [7, 10]. Here, m is the number of adjacent cores, L is the lightpath transmitting distance in kilometers, and h is the increase of the mean crosstalk per kilometer ($h > 0$). Eq. (2) defines h, which is determined by several fiber parameters: κ, β, ρ, and D corresponding to the coupling coefficient, propagation constant, bend radius and core-pitch, respectively [7, 10, 15]. The parameters for a seven-core MCF are presented in Table I.

$$XT(m, L) = \frac{m - m \cdot exp(-hL(m+1))}{1 + m \cdot exp(-hL(m+1))} \tag{1}$$

$$h = (2 \cdot \kappa^2 \cdot \rho)/(\beta \cdot D) \tag{2}$$

Eq. (3) is employed to find the relationship between XT and L. For a given core, $m > 0$ is fixed. Thus, XT is a nondecreasing function for a given core.

$$\frac{\partial XT}{\partial L} = m \cdot (m+1)^2 \cdot h \cdot exp(-hL(m+1)) > 0 \tag{3}$$

TABLE I
PARAMETERS FOR A SEVEN-CORE MCF

κ, coupling coefficient	$3.4 * 10^{-4}$
β, propagation constant	$4 * 10^{6}$ 1/m
ρ, bend radius	50 mm
D, core-pitch	$4.5 * 10^{-5}$ m
Θ, inter-core crosstalk threshold	-30 dB

B. Problem formulation

Notations (given):

- $\mathcal{G}(\mathcal{V}, \mathcal{E})$: $\mathcal{V}$ and $\mathcal{E}$ are sets of nodes and links in graph $\mathcal{G}$, respectively.
- $\mathcal{R}$: the set of requests.
- $r(o_i, t_i, b_i)$: the source node of the ith request is o_i, the set of target nodes is t_i, and the bandwidth requirement b_i in terms of FSs, $i \in \mathcal{R}$.
- $\mathcal{N}$: core fiber set, each link is equipped the same cores.
- B: total bandwidth requirement of anycast requests, $B = \sum_{i=1}^{|\mathcal{R}|} b_i$.
- FG: required FSs of a guard band for a request.
- $\mathcal{P}$: the set of routing paths $\mathcal{P} = \{p_{s,d}^{(k)}, \forall s \neq d \in \mathcal{V}\}$; k is used to index paths according to the ascending distance.
- F_{max}: an upper bound of the network capacity in terms of FSs with respect to $\mathcal{R}$, $F_{max} = B + FG \cdot |\mathcal{R}|$.
- m_v: the number of total adjacent cores of core v.
- Θ: inter-core crosstalk threshold.
- Ω_v: the maximum transmission distance of a lightpath in core v.
- $y_{i,j}$: relationship of lightpaths; it equals to 1 when the two lighpaths i and j are not link-disjoint; otherwise, it is 0 ($\forall i, j \in \mathcal{P}$).

Variables:

- $x_{i,p}$: a binary variable that equals to 1 if the ith request is provisioned by the pth path; otherwise, it is 0.
- f_i: an integer variable that defines the starting FS for the ith request, and the consecutively required bandwidth resources are also reserved for request i. Then, the spectrum contiguity constraint is automatically satisfied.
- $\zeta_{i,p}^{v}$: a binary variable that equals to 1 if the vth core is used by the pth path of the ith request; otherwise, it is 0 ($v \in \mathcal{N}$).
- $L_{i,p}^{v}$: an integer variable that equals to the length of the pth path of the ith request when the vth core is used.
- $z_{i,j}$: a binary variable that equals to 1 if the core selected for the ith request is the same as that for the jth request; otherwise, it is 0.
- $\delta_{i,j}$ ($\forall i \neq j$): it is a boolean variable which is defined in Eq. (4). It equals to 1 if the starting FS index f_j is bigger than that of f_i; otherwise, it is 0. Since this constraint is not linear, it is transformed to linear constraints as shown in Eqs. (10)-(12).

$$\delta_{i,j} = \begin{cases} 1, & f_i < f_j, \quad \forall i, j \in \mathcal{R} \\ 0, & f_i \geq f_j. \end{cases} \tag{4}$$

The ARSCA problem is formulated as follows. The objective is to minimize the maximum index of FSs in all cores among all links of the network, as expressed in Eq. (5). Eq. (6) imposes the constraint that each request should be provisioned with only one path. Eq. (7) is the FS contiguity constraint and ensures that consecutive FSs from f_i to $(f_i + b_i - 1)$ are assigned to the ith request, and the guard band FG is reserved after $(f_i + b_i - 1)$. Eq. (8) is the core assignment constraint, and it ensures only one core is assigned to each path. Eq. (9) is the inter-core crosstalk threshold constraint, and it ensures that the transmitted lightpath in a core can be demodulated in the receiver at the destination. Eqs. (10)-(12) represent the definitions of $\delta_{i,j}$, and they represent the starting FS index relationship between two different requests. Eqs. (13)-(14) are spectrum non-overlapping constraints.

$$\min_{x_{i,p},\zeta^v_{i,p},f_i} \quad F \tag{5}$$

$$s.t.:$$

$$\sum_p x_{i,p} = 1, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \tag{6}$$

$$f_i + b_i - 1 + FG \le F, \quad \forall i \in \mathcal{R} \tag{7}$$

$$x_{i,p} = \sum_v \zeta^v_{i,p}, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \tag{8}$$

$$XL(m_v, L^v_{i,p}) \le \Theta, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \tag{9}$$

$$f_j - f_i < \delta_{i,j} \cdot F_{max}, \quad \forall i \neq j \in \mathcal{R} \tag{10}$$

$$f_i - f_j < \delta_{j,i} \cdot F_{max}, \quad \forall i \neq j \in \mathcal{R} \tag{11}$$

$$\delta_{i,j} + \delta_{j,i} = 1, \quad \forall i \neq j \in \mathcal{R} \tag{12}$$

$$\begin{aligned} f_i + b_i - 1 + FG - f_j \le [5 - \delta_{i,j} - x_{i,p} - x_{j,p'} \\ - y_{i,j} - z_{i,j}] \cdot F_{max}, \quad \forall i, j \in \mathcal{R}, p \in \mathcal{P} \end{aligned} \tag{13}$$

$$\begin{aligned} f_j + b_j - 1 + FG - f_i \le [5 - \delta_{j,i} - x_{i,p} - x_{j,p'} \\ - y_{i,j} - z_{i,j}] \cdot F_{max}, \quad \forall i, j \in \mathcal{R}, p \in \mathcal{P} \end{aligned} \tag{14}$$

Note that Eq. (9) is not a linear constraint. Since XT is a nondecreasing function of the transmitting distance under a given core (Eq. (3)), Eq. (9) can be transformed into Eq. (15), which is a linear constraint.

$$L^v_{i,p} < \Omega_v \tag{15}$$

Since we employ a path-based method to formulate this problem, spectrum continuity constraints are already satisfied. An example to illustrate Eqs. (13)-(14) is shown as follows: If $\delta_{i,j} = 1, x_{i,p} = 1, x_{j,p'} = 1$, $y_{i,j} = 1$, and $z_{i,j} = 1$, it means that the selected two paths have joint links, the starting FS of f_j is bigger than f_i and these two requests are provisioned with the same cores; then, Eq. (13) is transformed into Eq. (16), which ensures the bandwidth non-overlapping constraint. Note that Eq. (14) is automatically satisfied in this case because F_{max} is the required bandwidth bound (a huge value).

$$f_i + b_i \le f_j \tag{16}$$

III. Heuristic Algorithm

The unicast RSA problem is proved to be an NP-hard problem [16], and the ARSCA problem can be mapped to the RSA problem if the set of destination nodes contains only one node and the number of cores reduces to one. Since the RSA problem is NP-hard, the ARSCA problem is also NP-hard. The optimal result cannot be easily achieved for large size problems because the computational complexity is exponentially increasing unless P=NP. We propose a heuristic algorithm named *ARSCA-SP*, which employs the shortest path and the predefined core prioritization reducing techniques [8].

Algorithm 1: ARSCA-SP Algorithm

Input : $\mathcal{G}(\mathcal{V}, \mathcal{E})$, $\mathcal{N}$, $\mathcal{R}$ and Θ;
Output: $x_{i,p}$, $\zeta^v_{i,p}$ and f_i;
1 **while** $\mathcal{R} \neq \varnothing$ **do**
2 set the core pattern with index according to the predefined reducing crosstalk algorithm in [8];
3 **for** *request* $r \in \mathcal{R}$ **do**
4 build shortest routing path set $\mathcal{P}_r$ from o_i to t_i for request r;
5 update the path set P according to Eq. (9);
6 get path $p \in \mathcal{P}_r$ with the shortest distance;
7 **for** *core* $v \in \mathcal{N}$ *along the path* p **do**
8 calculate the utilized FSs of core v along the path p;
9 get core v in the path p which has the lowest available FS index;
10 assign consecutive $b_i + FG$ FSs to the request r within the core v along path p;

Algorithm 1 shows the procedure of the *ARSCA-SP* algorithm. In the beginning, all cores are initialized with the “Predefined Core Prioritization Reducing Crosstalk” algorithm in [8] (*Line* 2). Here, all links are assumed to be equipped with seven-core MCFs. All anycast requests are provisioned one by one (*Lines* 3-10). A path set $\mathcal{P}_r$ is built for the rth request, and $\mathcal{P}_r$ is updated after checking Eq. (9) (*Lines* 4-5). Then, a core v in the path p with the lowest available FS index is chosen to provision the request r (*Lines* 7 - 9). In addition, the first fit strategy is used for making decision to choose FSs. The complexity of the *ARSCA-SP algorithm* is $O(|t_i|B|\mathcal{R}||\mathcal{E}|^2|\mathcal{N}|)$.

IV. Performance Evaluation

CVX [17] combined with Gurobi [18] and MATLAB are used to simulate the ILP strategy and the *ARSCA-SP algorithm*, respectively. For our minimization problem, CVX and Gurobi compute the gap between the incumbent value and upper bound, that guarantees the optimal result when the gap reduces to 0. All simulations are run on a Dell desktop with 3.4 GHz Intel Core i7-3770 CPU and 16 GB RAM.

The NSF network in Fig. 2 is used for the evaluation, and all links are MCFs. We assume BPSK modulation level is used, and the remaining simulation parameters are listed in Table II.

The objective and the runtime results with different numbers of requests are shown in Table III. The ARSCA-SP algorithm demonstrates a good performance, which provides results quite close to or the same as the optimal results provided by CVX within milliseconds. The maximum index of the used FSs and the core utilization results for all cores with 50 requests are shown in Fig. 3 and Fig. 4, respectively. Here, the core utilization is defined as the ratio of the utilized FSs in a core over the total FS requirement of all requests. The ARSCA-SP algorithm achieves nearly the same results as compared

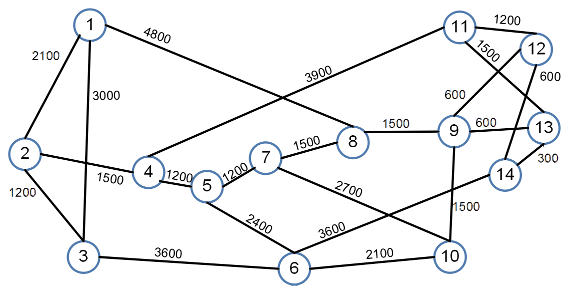

Fig. 2. A SDM EON with MCFs in the NSF topology (link lengh unit is kilometer).

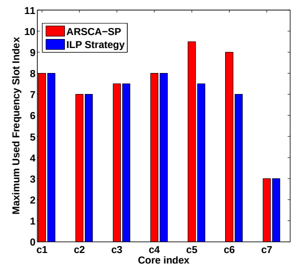

Fig. 3. Maximum used FS with 50 requests.

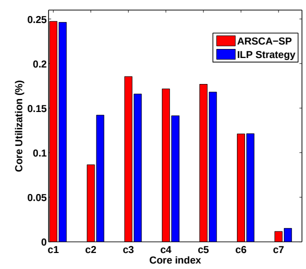

Fig. 4. Core utilization with 50 requests.

TABLE II
SIMULATION PARAMETERS FOR THE ARSCA PROBLEM

Network topology	NSF network
The bandwidth of a FS	12.5 Gb/s
o_i and t_i ($o_i \notin t_i$), randomly choose	$[1, 14]$
$\lvert t_i \rvert$, number of candidate destination nodes	2
b_i, the bandwidth requirement for $\mathcal{R}$	$[1, 8]$
F_G, guard-band FS per lightpath	1
$\lvert \mathcal{N} \rvert$, number of cores for each link	7
k, number of candidate paths for each request	3
$\lvert \mathcal{R} \rvert$, number of requests	$\{10, 20, 30, 40, 50\}$
Modulation level	BPSK, 1 bit/symbol

TABLE III
RESULTS FOR ARSCA IN THE NSF TOPOLOGY

	$\lvert\mathcal{R}\rvert = 10$		$\lvert\mathcal{R}\rvert = 20$		$\lvert\mathcal{R}\rvert = 30$		$\lvert\mathcal{R}\rvert = 40$		$\lvert\mathcal{R}\rvert = 50$	
	F	T†	F	T	F	T	F	T	F	T
ILP	8	83	8	802	8	3582	8	10721	8	25504
SP*	8	0.03	8	0.01	8	0.01	8	0.02	10.5	0.02

* It represents the ARSCA-SP algorithm.
† It stands for time consumption and the basic unit of T is one second.

to the ILP strategy for both the maximum index of used FSs and core utilization. Core 7 has the smallest maximum index in Fig. 3, and the maximum index for the other cores are nearly the same. In Fig. 4, core 1 has the highest utilization because of our predefined core index order and its having less adjacent cores, and core 7 has the lowest utilization because it has the most adjacent cores. Thus, the ARSCA-SP algorithm greatly explores the potential of MCFs as compared to the ILP strategy.

If we have MCFs with more than seven cores, for example, 12 cores [5], 22 cores [6] or even 32 cores, the ILP strategy and our algorithm always try to utilize the outer cores (which have the lowest crosstalk) first, then the middle layer cores, and finally the central layer cores.

V. CONCLUSION

This paper studies the anycast planning problem in SDM EONs overlaid on MCFs. The ARSCA problem is formulated by considering the core crosstalk using the ILP model. To our best knowledge, this is the first work to investigate the anycast problem in the space division multiplexing elastic optical networks overlaid on multicore fibers. CVX combined with Gurobi is used to achieve the optimal result, and we propose a heuristic algorithm, ARSCA-SP, to efficiently solve the ARSCA problem. The simulation results show that the ARSCA-SP algorithm provides results much faster and compatible to the CVX's solutions.

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