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

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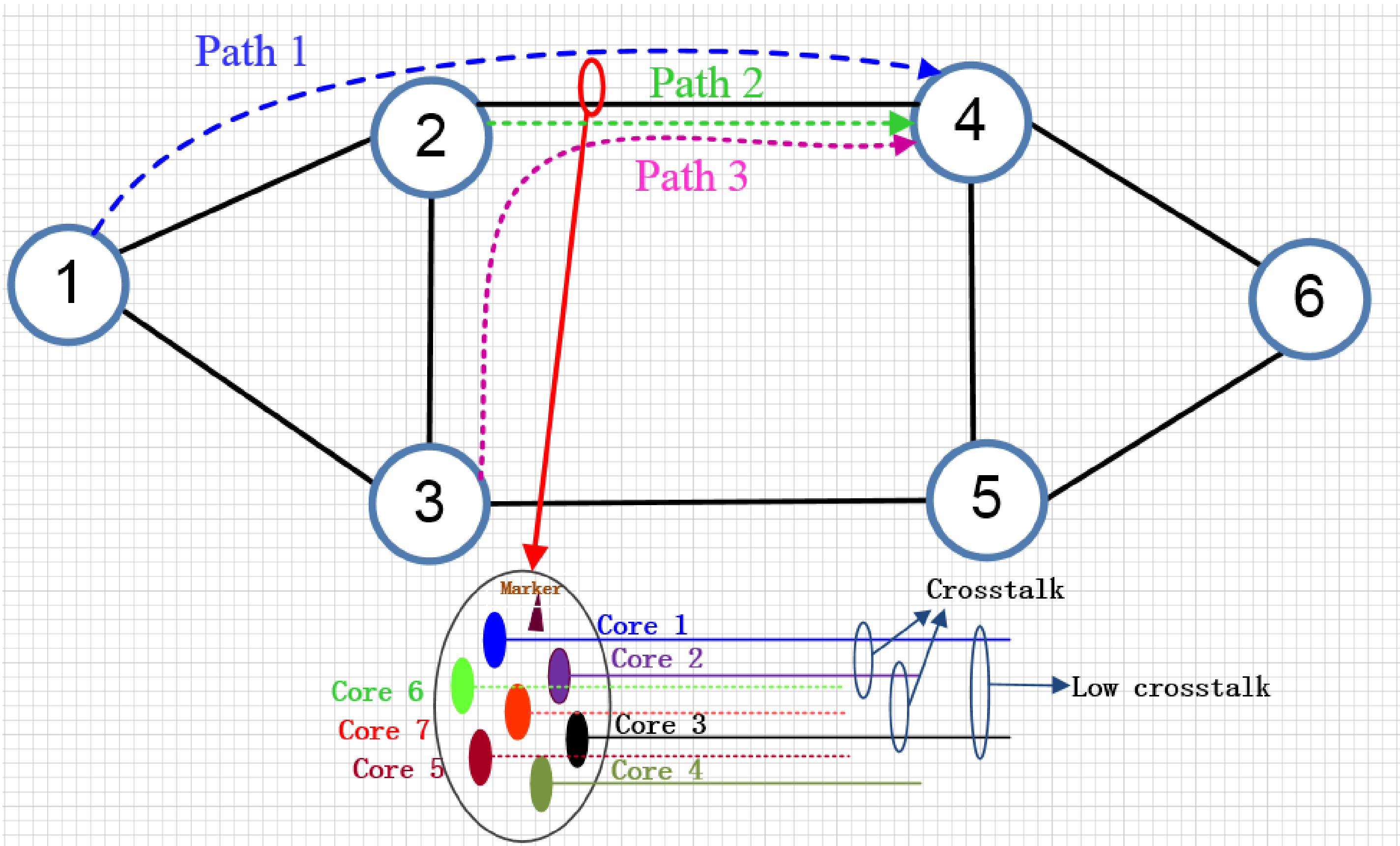
Outline

- Background
- Problem Formulation
- Heuristic Algorithm
- Evaluation Results
- Conclusions

SDM Elasctic Optical Neworks with MCFs



- Transmitting lightpath through the adjacent cores bring crosstalk to each other;
- The crosstalk between nonadjacent cores is too low to measure;
- The center core which has more adjacent cores exhibits higher crosstalk, and then the lightpath transmission distance in this core is shorter.

SDM Elasctic Optical Neworks with MCFs (cont'd)

Eq. (1) shows how to calculate the mean crosstalk of one core within a seven-core MCF [11]. Here, m is the number of adjacent cores, L is the lightpath transmitting distance in terms of kilometers, and h is the increase of the mean crosstalk per kilometer ($h > 0$). Eq. (2) shows the definition of h, and it is determined by several fiber parameters: κ, β, ρ, D which is the coupling coefficient, propagation constant, bend radius and core-pitch respectively [7, 11, 16]. The parameters for a seven-core MCF are set as Table I.

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

$$h = (2 \cdot \kappa^2 \cdot \rho)/(\beta \cdot D) \quad (2)$$

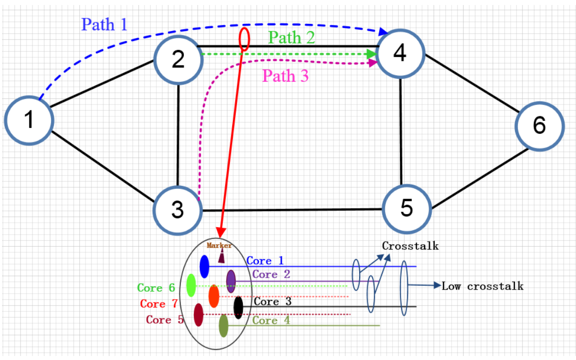


TABLE I
PARAMETERS FOR A SEVEN-CORE MCF

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

[7] A. Muhammad, G. Zervas, D. Simeonidou, and R. Forchheimer, "Routing, spectrum and core allocation in flexgrid SDM networks with multicore fibers," in *International Conference on Optical Network Design and Modeling*, pp. 192–197, May 2014.
[11] G. Saridis, D. Alexandropoulos, G. Zervas, and D. Simeonidou, "Survey and evaluation of space division multiplexing: From technologies to optical networks," *IEEE Communications Surveys Tutorials*, vol. 17, no. 4, pp. 2136–2156, Nov. 2015.
[16] T. Hayashi *et al.*, "Design and fabrication of ultra-low crosstalk and lowloss multi-core fiber," *Opt. Express*, vol. 19, no. 17, pp. 16 576–16 592, Aug. 2011.

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Notation

Topology

- $\mathcal{G}(\mathcal{V},\mathcal{E})$: $\mathcal{V}$ and $\mathcal{E}$ are node and link sets in graph $\mathcal{G}$, respectively.

Requests

- $\mathcal{R}$: requests set.
- $r(o_i, t_i, b_i)$: the source node of the ith request is o_i, the target node set is t_i, and the bandwidth requirement b_i in terms of FSs, $i \in \mathcal{R}$.

Core info.

- $\mathcal{N}$: core fiber set, each link is equipped the same cores.

Network bandwidth resource and path info.

- 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.
- $\mathcal{P}$: routing path set as $\mathcal{P} = \{p_{s,d}^{(k)}, \forall s \neq d \in \mathcal{V}\}$; 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 $\mathcal{R}$, $F_{max} = B + FG \cdot |\mathcal{R}|$.

Core and crosstalk parameters

- 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.

Relationship of links

- $y_{i,j}$: 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 it 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).

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

Problem Formulation

$$\min_{x_{i,p}, \zeta_{i,p}^{v}, f_i} \quad F \qquad (5)$$

Objective: minimize the maximum index of FSs in all cores among all links of the network

$s.t.:$

$$\sum_{p} x_{i,p} = 1, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \qquad (6)$$

one path serving constraint

$$f_i + b_i - 1 + FG \leq F, \quad \forall i \in \mathcal{R} \qquad (7)$$

FS contiguity constraint

$$x_{i,p} = \sum_{v} \zeta_{i,p}^{v}, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \qquad (8)$$

core assignment constraint

$$XL(m_v, L_{i,p}^{v}) \leq \Theta, \quad \forall i \in \mathcal{R}, p \in \mathcal{P} \qquad (9)$$

Crosstalk constraints

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

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

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

$$f_i + b_i - f_j \leq [5 - \delta_{i,j} - x_{i,p} - x_{j,p'} - y_{i,j} - z_{i,j}] \cdot F_{max} \quad \forall i, j \in \mathcal{R}, p \in \mathcal{P} \qquad (13)$$

$$f_j + b_j - f_i \leq [5 - \delta_{j,i} - x_{i,p} - x_{j,p'} - y_{i,j} - z_{i,j}] \cdot F_{max}, \quad \forall i, j \in \mathcal{R}, p \in \mathcal{P} \qquad (14)$$

non-overlapping constraints

Problem Formulation

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

$$h = (2 \cdot \kappa^2 \cdot \rho)/(\beta \cdot D) \quad (2)$$

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

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

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 to Eq. (15) which is a linear constraint.

$$L^v_{i,p} < \Omega_v \quad (15)$$

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Heuristic Algorithm

Algorithm 1: ARSCA-kSPP 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;

while $\mathcal{R} \neq \varnothing$ **do**
    set the core pattern with index according to the predefined reducing crosstalk algorithm in [9];
    for *request* $r \in \mathcal{R}$ **do**
        build k shortest routing path set $\mathcal{P}_r$ from o_i to t_i for request r;
        for *path* $p \in \mathcal{P}_r$ **do**
            check Eq. (9) for the path p;
            update the path set $\mathcal{P}_r$;
            for *core* $v \in \mathcal{N}$ **do**
                calculate utilized FSs of core v along the path p ;
        get core v in the path p which has the lowest available FS index;
        assign consecutive $b_i + FG$ FSs to the request r within the core v along path p;

The complexity of the ILP strategy and *ARSCA-kSPP algorithm* is $o(k^2B^2|\mathcal{R}|^2|\mathcal{E}|^4|\mathcal{N}|^2)$ and $o(kB|\mathcal{R}||\mathcal{E}|^2|\mathcal{N}|)$, respectively. *ARSCA-kSPP algorithm* greatly reduces the complexity.

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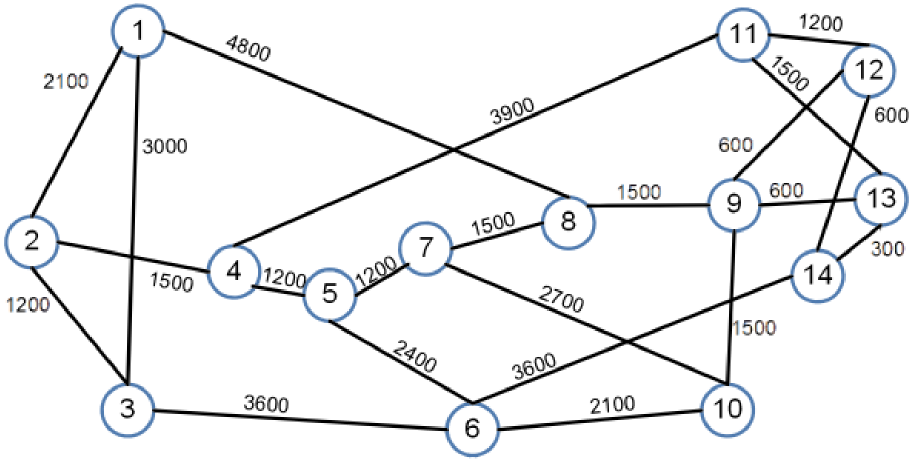
Simulation Settings



A SDM EON with MCFs in the NSF topology.

Table 1: Simulation Parameters

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 $\mathcal{R}$	$[1, 6]$
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	$\{5, 10, 20\}$
Modulation level	BPSK, 1 bit/symbol

Previous Evaluation Results

Table 2: Results for the ARSCA problem in the six-node topology

Algorithms	$\lvert\mathcal{R}\rvert = 5$, $B_t = 325$		$\lvert\mathcal{R}\rvert = 10$, $B_t = 637.5$		$\lvert\mathcal{R}\rvert = 20$, $B_t = 1212.5$	
	F	Time †	F	Time	F	Time
ILP (CVX)	8	151.42	8	2180.6	8	36928
ARSCA-SPP	8	0.04	8	0.05	11	0.06

† The basic unit of time is one second.

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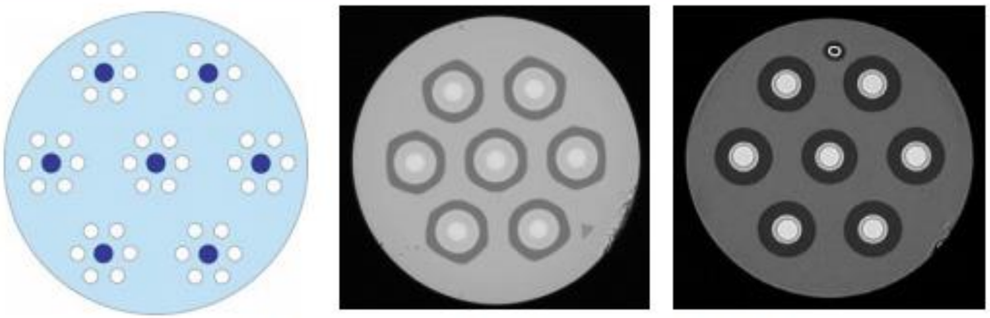
Conclusions

- This work studies the anycast planning problem in SDM EONs overlaid on MCFs. The ARSCA problem is formulated while considering the core crosstalk using ILP model.
- To our best knowledge, this is the first paper to investigate the anycast problem in the space division multiplexing elastic optical networks overlaid on multicore fibers.
- CVX and Gurobi are used to achieve the optimal result, and a heuristic algorithm named ARSCA-SPP is proposed to efficiently solve the ARSCA problem.

Multi-Core Fibers and Their Technical Feasibility



Uncoupled core MCF

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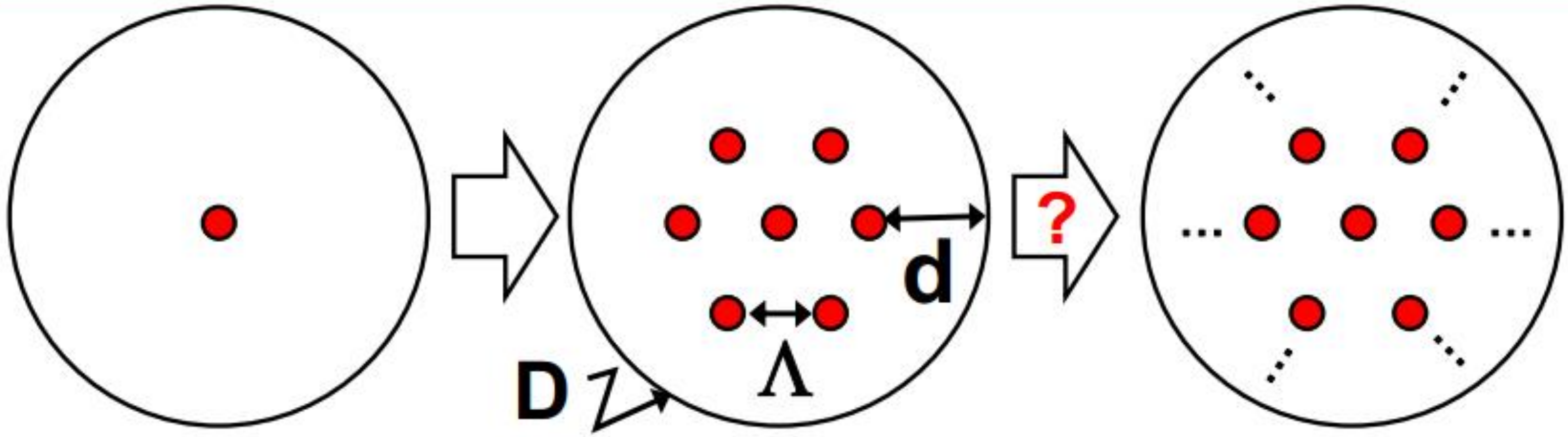
SUMITOMO ELECTRIC

1. Densely arranged cores



Single core fiber | 7-core fiber | More cores…

Items to be considered: Should design carefully considering crosstalk

Fiber structure

1) Core pitch : Λ
2) Cladding diameter : D
3) Core- outer cladding distance : d
4) Tight confinement into core

Condition of the evaluation

Fiber bend & twist

Other optical property?

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