Tridental Resource Assignment Algorithm for Spectrally-Spatially Flexible Optical Networks

Shrinivas Petale,[1] Juzi Zhao,[2] and Suresh Subramaniam[1]

[1]*Department of Electrical and Computer Engineering, The George Washington University, Washington, DC, USA*

[2]*Department of Electrical Engineering, San Jose State University, San Jose, CA, USA*

[1]{*srpetale,suresh*}*@gwu.edu*, [2]*juzi.zhao@sjsu.edu*

***Abstract*—Recent advances in Spectrally-Spatially Flexible Optical Networks (SS-FONs) have enhanced service provisioning by leveraging elastic optical transmission with a fine-grained and flexible frequency grid, multiple spatial modes (fiber cores), and a variety of advanced modulation formats (MFs) to increase the capacity of optical fiber. An important lightpath resource assignment problem in SS-FONs is the routing, modulation, core, and spectrum assignment (RMCSA) problem. Crosstalk (XT) between connections on different cores degrades the quality of transmission, and the RMCSA algorithm must ensure that XT constraints are met while maximizing performance. In this paper, we propose an RMCSA algorithm called Tridental Resource Assignment algorithm (TRA), as it balances three different factors that affect network performance. Our resource assignment approach includes both an offline/static network planning component and an online/dynamic provisioning component. In the former, MFs and spectrum utilization are used to compute path priorities for a lightpath. The dynamic provisioning component then allocates the resources on a selected path using TRA. Extensive simulation experiments performed in realistic network scenarios indicate that TRA significantly reduces the bandwidth blocking probability (BBP) in a variety of scenarios by maintaining a good balance between spectrum utilization and XT.**

I. Introduction

The staggering increase in bandwidth demands due to Internet-of-Things, 5G and 6G communications, cloud-based services, data center networks, and game streaming can be fulfilled by spectrally-spatially flexible optical networks (SS-FONs) [1]. Space division multiplexing (SDM) technology, along with elastic optical networking (EON), has allowed parallel transmission of optical signals through multicore fibers (MCF) with distance-adaptive multicarrier transmission [2], [3]. The quality of transmission of signals transmitted through MCF degrades due to the intercore crosstalk (XT) between weakly coupled cores [4], [5]. An important resource assignment problem in SS-FONs is the routing, modulation, core, and spectrum assignment (RMCSA) problem for dynamically arriving lightpath requests.

The effect of XT can be considered in various ways based on how XT constraints are used, e.g., [6]. The choice of significant threshold value based on practical norms is important [7]. Multipath routing is a suggested approach to reduce XT in [8]; however unbalanced load distribution makes resources scarce in certain areas of network. The effect of XT on an ongoing signal transmission also changes with respect to the selected modulation format (MF). The sensitivity of the MF decides its transmission reach (TR), which is defined as the maximum distance that the signal can be transmitted before it needs regeneration. Furthermore, if a sensitive MF is selected for a connection on a particular core, then the occupied spectrum on that core will not allow future connections to occupy any overlapping spectrum (OS) on the adjacent cores due to excessive XT. Thus, it is essential to handle the tradeoff between bandwidth utilization and XT levels to accommodate future requests. It can also be deduced that the effect of more sensitive MF gets magnified when a core with more adjacent cores is selected. Thus, the selection of core also plays an important role in reducing and avoiding the effect of XT.

In this paper, we propose an efficient RMCSA algorithm called as Tridental Resource Assignment algorithm (TRA). The word Tridental refers to the fact that the algorithm considers three factors of spectrum assignment that affect performance. TRA includes both an offline/static component and an online/dynamic component. The offline component involves the use of a mixed integer linear program (MILP) to obtain path priorities for a lightpath's route. The online component selects the path, core, MF, and spectrum for the arriving lightpath in an efficient manner.

The paper is organized as follows. The network model and problem statement are introduced in Section II. The path priority computation, and definitions, and details of the TRA algorithm are presented in Sections III, IV, and V. Section VI presents simulation results, and the last section concludes the work.

II. Network Model and Problem Statement

We assume that the SS-FON operates with a flexible grid of 12.5 GHz granularity and is equipped with coherent transceivers (TRXs). The TRXs support reconfigurable bit-rates and various MFs. The TRXs operate at a fixed baud rate of 14 GBaud, and each TRX transmits/receives an optical carrier allocated on 2 frequency slices (FSs) (i.e., 25 GHz). If the requested bit-rate exceeds the maximum capacity of a single TRX using a particular MF, the request is carried by several optical carriers within one superchannel (SCh). Each SCh is separated from neighbor SChs by 12.5 GHz guard-bands. The nodes are connected using optical links consisting of MCFs. Each fiber link consists of the same set of MCFs with a specified core geometry in both the directions[1]. Two challenging and widely accepted core geometries, 3-core and 7-core [9], are studied. The effect of XT is dominant between the cores which are right next to each other called as *adjacent/neighbor cores*. For

[1]In this paper, we assume that all the links have a single MCF in each direction, but the proposed work can be easily generalized for multiple fibers per link.

instance, each core in a 3-core fiber has two adjacent cores. Similarly, in 7-core fiber, the outer cores have three adjacent cores and the center core has six adjacent cores (see Fig. 1). Furthermore, spatial continuity is imposed which means that the same core is assigned to a lightpath on all MCF links on a route. Lightpath requests arrive at a specified Poisson rate with exponentially distributed mean holding time of unity (arbitrary units) and the datarates are uniformly distributed over a given range.

The XT model of [10] is used to obtain the TRs for various MFs and for various values of lit adjacent cores (or litcores for short), as shown in Table II (from [11]). We consider average XT values of -25 dB [12] and -40 dB between two adjacent cores after a single span of propagation [11]. The total XT experienced by a core is the sum of individual average XT contributions from each neighbor. The number of allowable lit cores is denoted as γ. The γ for MF of an existing connection on a core decides the allowable occupancy of adjacent cores on the OS, thus high value of γ is desired. For incoming connection request, γ of candidate MF decides whether the spectrum can be occupied with this MF based on occupancy of OS on adjacent cores. With an increase in γ value, the XT level experienced by the core increases resulting in shorter TRs. Hence, for a longer path if a higher MF is chosen, the gamma value will be low. Thus, although a higher MF saves spectrum, it blocks the occupancy of OS on adjacent cores. For the same path if a lower MF is chosen, more spectrum will be required but the OS on adjacent cores will be allowed to be occupied due to larger γ. The objective of our RMCSA problem is to decrease the bandwidth blocking probability (BBP) by maintaining a proper balance between spectrum utilization and XT level.

Table I: Symbols and notations.

Symbol	Definition
N	Number of nodes in the network
L	Number of links in the network
e	Arbitrary network link
R	Number of routes in the networks
r	Arbitrary route
W_r	Load for route r; depends on the traffic pattern; W_r = 1, $\forall$ r for uniform traffic
M	Set of connection sizes $\{m_1, m_2, \ldots, m_{\|M\|}\}$
m_i	i^{th} datarate in Gbps
ρ_i	Probability that arbitrary request has rate m_i; $\sum_{i=1}^{\|M\|} \rho_i$ = 1
C	Number of cores per fiber
K	Number of shortest paths considered for a route
k	Arbitrary candidate path
Bw	Total spectrum available in GHz
δ	Slice width in GHz
$A^e_{r,k}$	= 1 if link e is on the k^{th} candidate path of route r; = 0, otherwise
η^k_r	Spectral efficiency of selected modulation format for k^{th} candidate path of route r
g_b	Number of guard bands of size δ GHz
N^k_r	Number of FSs required on k^{th} shortest path of route r, $$N^k_r = \sum_{i=1}^{\|M\|} \rho_i \left(\left\lceil \frac{m_i}{\delta \eta^k_r} \right\rceil + g_b \right) \quad (1)$$
$R^e_{r,k}$	Fraction of FSs utilized on link e on k^{th} candidate path of route r, $$R^e_{r,k} = A^e_{r,k} N^k_r \quad (2)$$

III. Priority-based Multipath Selection

In this offline method, we calculate priorities for the multiple candidate paths for every source-destination (s-d) pair or route. These priorities will be used to select the path in online resource assignment as explained in the following sections. Path priorities are based on path probabilities that optimize the link load. Notations and symbols are defined in Table IK shortest paths for each s-d pair are pre-computed, and an MILP is solved offline to determine the path probabilities, similar to our previous work [13]. The shortest paths are prioritized from higher to lower path probabilities for assignment called as priority-based path selection (PPS). The objective (z_{fs}) of the MILP is to minimize the sum of average link load and maximum link load as shown in (3). The probability of selecting the k^{th} candidate path of route r is denoted as p^k_r as shown in (4a) and (5a). u^e_r is defined as the spectrum requirement on link e by route r as shown in (4b) and (5b).[2]

$$\text{Minimize } z_{fs} = \frac{1}{L} \sum_{e=1}^{L} \sum_{r=1}^{R} W_r u^e_r + \max_{e} \sum_{r=1}^{R} W_r u^e_r \quad (3)$$

Variables:

$$0 \leq p^k_r \leq 1, \quad 0 \leq u^e_r \leq \left\lfloor \frac{Bw}{\delta} \right\rfloor. \quad \text{(4a-b)}$$

Constraints:

$$\sum_{k=1}^{K} p^k_r = 1, \quad u^e_r = \sum_{k=1}^{K} R^e_{r,k} p^k_r. \quad \text{(5a-b)}$$

IV. Network Capacity, Capacity Loss and Tridental Coefficient

In this section, we define some of the quantities used in TRA and present an example to illustrate how these are computed. We call a set of FSs as a slice window (SW). The aim of TRA is to choose the best SW along with the MF and core to yield the best blocking performance. On shortest path k of route r, namely r^k, there are a number of SWs, with the first one having starting FS of 1, the second SW with starting FS of 2, and so on. The *capacity, capacity loss (CL),* and *tridental coefficient (TC)* of a candidate SW are defined as follows.

A. Capacity of an SW

The capacity of the n^{th} SW on r^k for a given MF f_d, denoted by $\upsilon^{k,d}_n$, is the number of cores on the whole path on which the SW can be assigned in the current network state (i.e., before resource assignment for the incoming request). Here, the current network state includes the litcore restriction of the already established connections on OS on adjacent cores. When SW is assigned to the incoming request on a core with MF f_d, the capacity would decrease by an amount that depends on f_d and its corresponding allowable γ for the length of the lightpath. Thus, the remaining capacity of the n^{th} SW on c^{th} core on r^k using f_d, denoted as $\upsilon'^{k,d}_{n,c}$, is the capacity of the SW *if it were to be assigned to the incoming request*, with the actual value of γ of selected MF f_d, denoted as γ_d, and the actual network state.

[2]We assume in this offline calculation that the highest possible MF for the length of the path is used to calculate the number of FSs.

B. Capacity Loss and Tridental Coefficient of a Slice Window

The remaining capacity of a SW after the resource assignment of a connection varies based on the selected core and XT tolerance of the selected MF f_d. Thus, for every core and MF pair, $\upsilon'^{k,d}_{n,c}$ varies. In this paper, we calculate the capacity loss (CL) for every SW based on the hypothetical assignment of the core, MF, and SW for the incoming request. The decrease in capacity after the hypothetical provisioning from the capacity before provisioning gives the total CL. If the XT constraints are removed, CL for a particular selection of SW for a core on a route is one. However in SDM EON, the XT tolerance of the selected MF on a core decides the future occupancy on adjacent cores, thus the CL can be more than one. Finally, the CL for the n^{th} SW on c^{th} core on r^k using f_d is calculated using (6).

$$\psi^{k,d}_{n,c} = \upsilon^{k,d}_{n} - \upsilon'^{k,d}_{n,c}. \tag{6}$$

The optimal choice of spectrum is when shared resources in the network are still available for future demands. When an SW on a path is assigned to a request, there is a CL for the SW on all the overlapping (shared) paths as well. Thus, we consider the network occupancy by calculating the CL of the same SW on all the shared paths. The CL for the incoming request's path and the shared paths are weighted with the corresponding path probabilities (PP) (see Eq. 4a) to get the total CL.

Let, Z be the set of all the shared paths; $Z = i_1, i_2, \ldots, i_z$. The PP of r^k is denoted as p^k_r and of i_z is denoted as p_z, obtained in Section III. Suppose that the incoming request has datarate m and arrived on route r, and is denoted by $\Delta(r, m)$. The number of FSs required to accommodate datarate m using MF f_d is denoted as β^m_d. We assume a lightpath tuple, $l_{\Delta(r,m)}(k, c, n, \beta^m_d)$, which represents the n^{th} SW of size β^m_d on c^{th} core on r^k for request $\Delta(r, m)$. The total CL of $l_{\Delta(r,m)}(k, c, n, \beta^m_d)$ is shown in (7); where, $\psi^{r\,k,d}_{\;n,c}$ is the CL ($\psi^{k,d}_{n,c}$) on r^k and $\psi^{i\,z,d}_{\;n,c}$ is the CL ($\psi^{k,d}_{n,c}$) on the z^{th} shared path i_z ($i_z \in Z$).

The CL of an SW estimates how much loss in capacity (including the effects of XT) is incurred if that SW is assigned to the incoming request. However, prior research has shown that it is important to consider the amount of spectrum assigned to the connection as well as spectrum fragmentation caused by an assignment. It is generally known that the first fit spectrum assignment decreases fragmentation. In order to capture these effects, we consider two more factors besides CL, in the definition of TC.

The TC of $l_{\Delta(r,m)}$ is defined as the sum of normalized values of CL, size of SW in terms of number of FSs, and the starting index of SW. It is denoted as $\Psi(l_{\Delta(r,m)})$ and is given in (8). The normalization is done using the respective maximum and minimum values, viz., maximum possible CL denoted by $\max \psi'(l_{\Delta(r,m)})$ (minimum is 0), largest and smallest possible demandsize of datarate m denoted as β^m_1 and $\beta^m_{|D|}$, respectively, and highest and lowest possible index of a SW is equal to $S - \beta^m_d + 1$ and 1, respectively. $\max \psi'(l_{\Delta(r,m)})$ is obtained offline using PPs and assuming maximum CL, which is equal to C, on main route and shared paths. The consideration of normalized CL ensures that the least lossy SW is selected. The normalized demandsize ensures that low spectrum utilization is favored. Finally, the normalized index of SW encourages the first-fit behavior which decreases fragmentation.

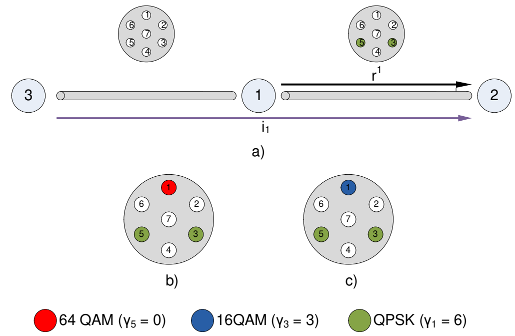


Figure 1: Effect of selection of two different MFs on capacity.

$$\psi'(l_{\Delta(r,m)}) = p^k_r \psi^{r\,k,d}_{\;n,c} + \sum_{z=1}^{|Z^k|} p_z \psi^{i\,z,d}_{\;n,c}. \tag{7}$$

$$\Psi(l_{\Delta(r,m)}) = \frac{\psi'(l_{\Delta(r,m)})}{\max \psi'(l_{\Delta(r,m)})} + \frac{\beta^m_d - \beta^m_{|D|}}{\beta^m_1 - \beta^m_{|D|}} + \frac{n-1}{S - \beta^m_d}. \tag{8}$$

C. An Illustrative Example

Table II: Transmission reaches of MFs for different values of allowable lit core (γ) from Table II in [11]

	Modulation Formats ($\|D\| = 5$, $f_d \in D$)				
γ (Litcores)	**QPSK**	**8 QAM**	**16 QAM**	**32 QAM**	**64 QAM**
0	9050	3600	1950	1000	500
1	1350	500	250	150	50
2	700	250	150	50	0
3	450	200	100	50	0
4	350	150	50	0	0
5	300	100	50	0	0
6	250	100	50	0	0

We illustrate the calculations of CL and TC for the first SW (n = 1) on core 1 of a 7-core fiber for two different candidate MFs on the main route with the help of an example shown in Fig. 1 and Table II. D is the set of MFs $\{f_1, f_2, \ldots, f_{|D|}\}$. In this example, we assume that $|D| = 5$ and used 64 QAM (f_5) and 16 QAM (f_3) for the explanation. We use Table II to get γ_d of both the MFs. Table II reports the TRs calculated for the combination of MF and number of adjacent litcores (γ) for the TRX baudrate of 14 GBaud and XT threshold (XT^{th}) of -25 dB. The number of litcores varies from 0 to 6 in a 7-core fiber, thus TRs are given for each MF for $\gamma = 0, \ldots, 6$. The corresponding value of γ for which the TR of an MF is greater than or equal to the path length is chosen as γ_d for a given MF on this path.

Assume that the first SP on route r, r^1 from node 1 to 2, has the highest priority and i_1 from node 3 to 2 is the path sharing a link with r^1. r^1, i_1, and the occupancy of cores on each link are shown in Fig. 1a. Assume that both r^1 and i_1 have the same PP of 0.6. Suppose that the first 20 FSs out of $S = 320$ FSs on cores 3 and 5 are occupied by a connection which uses QPSK (f_1) with γ_1=6, and the FSs on the other cores are free. Suppose a connection request of 120 Gb/s arrives on r, and the length of r^1 is 54 km which requires β^m_5=2 FSs, β^m_3=5 FSs and β^m_1=7 FSs when 64 QAM (f_5), 16 QAM (f_3) and QPSK

(f_1) are chosen. The first SW (n=1) for 64 QAM is of size β_5^m FSs and for 16 QAM is of size β_3^m. In both the cases, the SW of respective sizes is free on cores 1, 2, 4, 6 and 7, i.e., the capacity before any assignment in both the cases is 5, i.e., $\upsilon_1^{1,5}$=$\upsilon_1^{1,3}$=5. The hypothetical assignment is done to see the remaining capacity after a selection of the MF. Starting from the highest MF, i.e., 64 QAM (f_5), the hypothetical assignment is done on core 1 as shown in Fig. 1b. From Table II for 64 QAM, as the first TR, searched from the bottom to the top, at γ=0 (500 Km) is higher than path length (54 Km), γ_5 is set to 0. It means that based on XT tolerance of 64 QAM, if assigned for the current connection on core 1, the connection will not allow adjacent cores 2, 6, and 7 to be assigned to future requests on the OS as long as it exists in the network. Thus, OS only on core 4 will be available for future connections, which means that the capacity after hypothetical assignment with 64 QAM is 1, i.e., $\upsilon'^{1,5}_{1,1}$=1. Thus using (6), CL ${\psi^r}^{1,5}_{1,1}$ in this case is $\upsilon_1^{1,5} - \upsilon'^{1,5}_{1,1}$=5-1=4. Assume that the same CL occurs at i_1, i.e., ${\psi^i}^{1,5}_{1,1}$=4. Thus, using (7), the total CL ($\psi'(l_{\Delta(r,m)})$) with 64 QAM is 0.6×4+0.6×4=4.8. Let us suppose that the maximum value of total CL ($\max \psi'(l_{\Delta(r,m)})$) is 10. Thus, the TC of the first SW with 64 QAM ($\Psi(l_{\Delta(r,m)})$), by substituting the values in (8), is $\frac{4.8}{10}$+$\frac{2-2}{7-2}$+$\frac{1-1}{320-2}$=0.48. Similarly, for the first SW of size β_3^m with 16 QAM, from Table II, we get γ_3=3, i.e., if assigned, it will allow the OS to occupy on the adjacent cores 2, 6 and 7 by future requests as long as it remains in the network. Thus, OS on cores 2, 4, 6, and 7 will be available for future connections. Thus, the capacity after hypothetical assignment with 16 QAM is 4, i.e., $\upsilon'^{1,3}_{1,1}$=4. Thus CL ${\psi^r}^{1,3}_{1,1}$ in this case is $\upsilon_1^{1,3} - \upsilon'^{1,3}_{1,1}$=5-4=1. Assume that the same CL occurs at i_1, i.e., ${\psi^i}^{1,3}_{1,1}$=1. The total CL ($\psi'(l_{\Delta(r,m)})$) with 16 QAM is 0.6×1+0.6×1=1.2. Using (8), the TC of the first SW with 16 QAM ($\Psi(l_{\Delta(r,m)})$) is $\frac{1.2}{10}$+$\frac{5-2}{7-2}$+$\frac{1-1}{320-2}$=0.72.

V. Tridental Resource Assignment (TRA)

We now describe our proposed TRA algorithm. First, we define an available SW (which is a candidate SW for assignment).

Definition V.1 (Available Slice Window)**.** An SW of size β_d^m is called available SW for assignment to a connection request with datarate m on route r, denoted as $\Delta(r,m)$, using MF f_d on core c on all the links on a given SP of route r $\iff$ all the FSs from index n to n+$\beta_d^m - 1$, on the core c on all the links of given SP of route r, a) are free, i.e., not assigned to any other connection, b) can accommodate $\Delta(r,m)$ without affecting ongoing connections on OS on adjacent cores of core c, and c) can accommodate $\Delta(r,m)$ based on XT sensitivity of MF f_d.

As spatial continuity is imposed, a FS on a core is considered as free only if it is free on the same core index on all the links on the path. The second condition is satisfied by checking the maximum value of allowable γ over all the overlapping FSs in an SW on each of the adjacent cores on all the links. In other words, the ongoing connections on the adjacent cores should allow the new connection to be placed on the current core. In the third condition, the maximum value of occupied cores over all the FSs in an SW over all the links should be less than or equal to the obtained γ_d.

Algorithm 1 TRA Algorithm

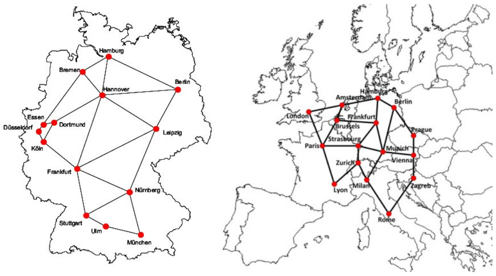
Input: Network topology, $\Delta(r,m)$, set of SPs $P(r)$, their path lengths l_r^k and path probabilities p_r^k, V^m, H^m

Output: $l^*_{\Delta(r,m)}(k^*, c^*, n^*, \beta^*)$

```
1: l*_Δ(r,m) ← ∅, Ψ(l*_Δ(r,m)) ← ∞, k ← 1
2: while l*_Δ(r,m) = ∅ ∧ k ≠ K do
3:     for all (f_d ∈ D ∧ T_d^0 ≥ l_r^k) do
4:         lit core γ_d ← γ for which T_d^γ ≥ l_r^k
5:         Get β_d^m, β_1^m and β_|D|^m from V^m
6:         for all b_{c,n}^{m,d} ∈ B_d^m, B_d^m ∈ H^m do
7:             lightpath l_Δ(r,m) ← (k, c, n, β_d^m)
8:             if SW is available then
9:                 Calculate Ψ(l_Δ(r,m)) of b_{c,n}^{m,d} SW
10:                if Ψ(l_Δ(r,m)) < Ψ(l*_Δ(r,m)) then
11:                    l*_Δ(r,m) ← l_Δ(r,m), k* ← k, c* ← c, n* ← n,
                       β* ← β_d^m
12:                end if
13:            end if
14:        end for
15:    end for
16:    if l* = ∅ then
17:        k ← k + 1
18:    end if
19: end while=0
```

All the possible SWs of spectrum for datarate m using MF f_d on all the cores are stored in set B_d^m. While selecting core and spectrum, switching cores before frequency gives better results [14], [15]. Thus, the SWs are stored in such a way that starting from the lowest index of SW, the choices of SW on all the cores are stored in the increasing order of core index before moving to the next SW. For datarate m, H^m is the set of all B_d^m sets for all MFs. The SW of index n on core c in B_d^m is denoted by $b_{c,n}^{m,d}$. For the datarate m, V^m is the set of β_d^m for all MFs.

The selection of a path, MF, core, and SW by TRA for a lightpath is explained in Algorithm 1. For simplicity, we assume that the SPs are sorted and renumbered as per the corresponding value of PP p_r^k from highest (k = 1) to lowest (k = K). The TR of MF f_d for the corresponding value of γ is denoted as T_d^γ. The optimal lightpath $l^*_{\Delta(c,m)}(k^*, c^*, n^*, \beta^*)$ and its corresponding TC are initialized in Line 1. Here, the desired path index, core index, index of SW and demandsize are denoted by k^*, c^*, n^*, and β^*. The SP with highest PP is chosen in Line 1. In Line 2, the algorithm continues until either the SW with the lowest (best) TC is found or the search over all the SPs is completed. In Line 3, the search is initiated for those MFs whose maximum TR, i.e., TR without the consideration of XT at $\gamma = 0$ (T_d^0) is higher than path length of the k^{th} SP. In Line 4, the allowable litcore value γ_d is the γ value for which the TR value T_d^γ is the path length of the k^{th} SP. In Line 5, the actual, largest and smallest sizes of SW are obtained. In Line 6, loop iterating over all the choices of SWs in B_d^m is started. The candidate lightpath l is initiated in Line 7. If the SW is available as per definition,



(a) (b)

Figure 2: Network topologies.

the TC is calculated for the current SW $b_{c,n}^{m,d}$ on lightpath l in Line 9. In Lines 10-12, the information of SW which offers the least value of TC is stored as the desired lightpath l^*. In Line 17, the algorithm checks whether the desired lightpath $l^*_{\Delta(r,m)}$ is obtained or not. If it is obtained then the algorithm stops. Otherwise, the algorithm continues with the next SP in Line 17. Finally, after all the SWs on all the cores on the whole path are processed, the optimal lightpath $l^*_{\Delta(r,m)}$ is selected for a given connection, and the network resources are assigned to the connection request accordingly. If an SW is not found on all the SPs (i.e., $l^*_{\Delta(r,m)} = \varnothing$), the request is rejected.

VI. Simulation Results

We now present simulation results comparing TRA with several other algorithms for a variety of scenarios. We use two practical topologies: generic German (DT) and European (EURO) shown in Fig. 2. The spectrum of 4 THz (Bw = 4000) is considered on each link with each slice of 12.5 GHz (δ = 12.5) i.e., 320 FSs (S = 320). Poisson connection arrival process with exponentially distributed holding time of 1 (arbitrary time unit) is assumed. The Erlang loads were chosen so that the BBP values generally range between 10^{-5} and 10^{-1}. A total of 100,000 requests are generated per trial, with the first 10,000 warm up requests being discarded. 95% confidence intervals are also obtained for each experiment. The data rates are uniformly distributed between 40-400 Gbps with the granularity of 40 Gbps. There exist 3 SPs between every s-d pair (K = 3). Total of five MFs ($|D|$ = 5), i.e., f_1 to f_5 are used viz., QPSK, 8 QAM, 16 QAM, 32 QAM and 64 QAM. The TR model for each MF with the XT per span of -25 dB and -40 dB with 14 GBaud TRX with the span length of 50 km is used from [11].

We compare the performance of TRA with a baseline XT-aware first fit algorithm (xtFF), and two algorithms from the literature, KCAP [16] and P-XT [9]. The KSP routing is used with these algorithms while PPS is used with TRA. The transmission reach model for a given XT^{th} value is the same for all the algorithms. The results are presented for K=3, but similar trends are seen for higher values, e.g., K=6. xtFF chooses the highest MF and the first available SW for assignment. KCAP is a path priority-based core and spectrum assignment algorithm. The cores are divided into groups and the path-core pairs are searched in the increasing order of required FSs which are obtained using TR model for every group. P-XT does a XT-aware spectrum assignment with exhaustive search on all the routes. The spectrum available on the earliest index among the ones available on all the paths is selected. The algorithms are compared for the same parameters; especially, for the same XT^{th}, with imposed spatial continuity constraint, and spectrum choices available for spectrum search.

The comparison of TRA with other algorithms in terms of BBP is shown in Fig. 3, and in terms of utilization of MFs and SPs is shown in Fig. 4. In Fig. 4, the first set of four bars for each algorithm indicate the % utilization of MFs, mentioned as ':MF', and the second set of four bars indicate the % utilization of SPs, mentioned as ':SP'. In Fig. 3a-3b, the performance of algorithm for XT^{th}=-25dB is shown for C=3 and C=7 in DT network topology. TRA outperforms the rest of the algorithms by a huge margin (by a few orders of magnitude of BBP in many cases) for both the core types.[3] It is because of the proper selection of SWs with the consideration of XT. In addition, the distribution of utilized MFs for XT^{th}=-25 dB with C = 3 for DT is shown in Fig. 4a. Every MF is utilized by TRA unlike other algorithms which exploit only one or two MFs. Proper selection of MFs manifests itself as reduced BBP, because when a more XT-sensitive MF is chosen it may save spectrum but prevents future connections to be assigned on OS on adjacent cores. As shown on the second bar of TRA, TRA:SP, in Fig. 4a, it is clear that the search space from the available number of SPs is reduced by TRA and almost all the connections are established on the first path. This is because the use of calculated PP makes TRA to distribute the network load properly in a XT environment even though the calculation of PP does not consider XT (as it is done offline). The use of SPs is more in case of P-XT because it focuses on searching for the lowest index of FS on all the SPs. Similar to TRA, a similar distribution of SPs is seen for xtFF, however, the selection of SW is not effective and thus it results in high BBP.

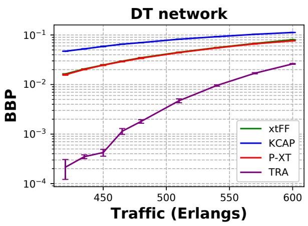
The performance of TRA is also better when XT^{th}=-40 dB is chosen for C=3 and C=7 as shown in Fig. 3c and Fig. 3d. Similar to TRA, the performance of KCAP is significantly improved in the case of XT^{th}=-40 dB as compared to XT^{th}=-25 dB. This is because, as TR values are higher due to reduced XT, higher MFs are chosen more often which saves spectrum. The observed distribution of MFs for KCAP is similar to that of TRA (not shown here) which results in improvement in its performance as shown in Fig. 3c as compared to its performance when XT^{th}=-25dB as shown in Fig. 3a.

Similar performance is observed in the EURO topology with a slight difference in terms of BBP for the XT^{th}=-25 dB with C=3 (Fig. 3e) and C=7 (Fig. 3f) as well as for XT^{th}=-40 dB with C=3 (Fig. 3g) and C=7 (Fig. 3h). There is also a difference in the distribution of MFs for XT^{th}=-25 dB and XT^{th}=-40 dB as shown in Fig. 4b. This is because EURO has longer path lengths with more hops compared to the DT topology. It is evident from the performance evaluation that TRA efficiently balances the tradeoff among various factors for different core geometries and path lengths in different topologies.

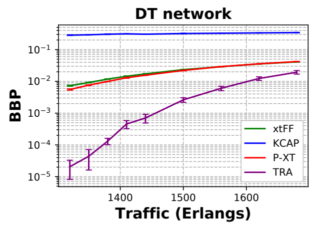
VII. Conclusion

We addressed the dynamic RMCSA problem in spectrally-spatially flexible optical networks. Inter-core crosstalk is an im-

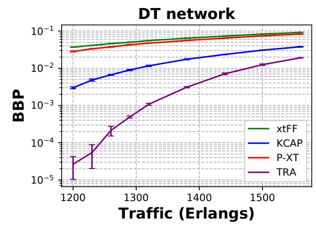
[3] Note that some BBP values are lower than 10^{-5} because some trials gave 0 blocked requests at loads.



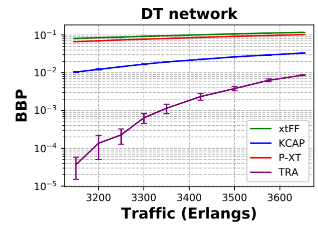
(a) XT^{th} = -25dB, C = 3



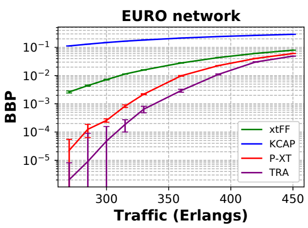
(b) XT^{th} = -25dB, C = 7



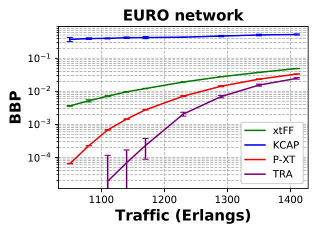
(c) XT^{th} = -40dB, C = 3



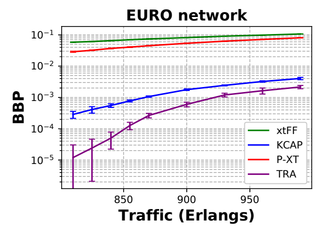
(d) XT^{th} = -40dB, C = 7



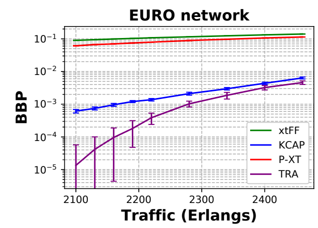
(e) XT^{th} = -25dB, C = 3



(f) XT^{th} = -25dB, C = 7

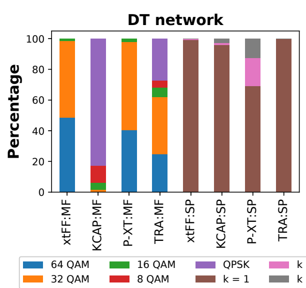


(g) XT^{th} = -40dB, C = 3

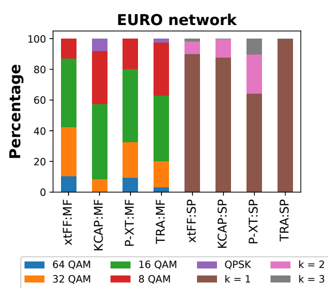


(h) XT^{th} = -40dB, C = 7

Figure 3: Variation in BBP wrt traffic for different XT^{th} values.



(a) XT^{th} = -25dB, C = 3



(b) XT^{th} = -40dB, C = 7

Figure 4: Distribution of used MFs and K SPs for different XT^{th} and C values.

portant consideration in MCF SDM networks, and we proposed an RMCSA algorithm called as Tridental Resource Allocation (TRA) algorithm which achieves a good balance between spectrum utilization and crosstalk levels in the network. It considers network occupancy to calculate the capacity loss and select the slice window which has the least effect on the network for future connections. It properly handles the tradeoff between spectrum utilization and crosstalk tolerance by using the effect of crosstalk in the calculation of loss of capacity. Extensive simulation results show the vastly improved performance of TRA over algorithms in the literature.

Acknowledgement This work was supported in part by NSF grants CNS-1813617 and CNS-1813772.

References

[1] B. Shariati, D. Klonidis, I. Tomkos, D. Marom, M. Blau, S. Ben-Ezra, M. Gerola, D. Siracusa, J. Macdonald, N. Psaila, *et al.*, "Realizing spectrally-spatially flexible optical networks," *IEEE Photon, Society Newsletter*, pp. 4–9, 2017.

[2] Y. Awaji, J. Sakaguchi, B. J. Puttnam, R. S. Luís, J. M. D. Mendinueta, W. Klaus, and N. Wada, "High-capacity transmission over multi-core fibers," *Optical Fiber Technology*, vol. 35, pp. 100–107, 2017.

[3] G. M. 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, 2015.

[4] M. Klinkowski, P. Lechowicz, and K. Walkowiak, "Survey of resource allocation schemes and algorithms in spectrally-spatially flexible optical networking," *Optical Switching and Networking*, vol. 27, pp. 58–78, 2018.

[5] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Optics express*, vol. 19, no. 17, pp. 16576–16592, 2011.

[6] M. Yang, Y. Zhang, and Q. Wu, "Routing, spectrum, and core assignment in sdm-eons with mcf: node-arc ilp/milp methods and an efficient xt-aware heuristic algorithm," *Journal of Optical Communications and Networking*, vol. 10, no. 3, pp. 195–208, 2018.

[7] L. Zhang, N. Ansari, and A. Khreishah, "Anycast planning in space division multiplexing elastic optical networks with multi-core fibers," *IEEE Communications Letters*, vol. 20, no. 10, pp. 1983–1986, 2016.

[8] H. M. Oliveira and N. L. da Fonseca, "Multipath routing, spectrum and core allocation in protected sdm elastic optical networks," in *2019 IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, IEEE, 2019.

[9] M. Klinkowski and G. Zalewski, "Dynamic crosstalk-aware lightpath provisioning in spectrally-spatially flexible optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 11, no. 5, pp. 213–225, 2019.

[10] P. Poggiolini, "The gn model of non-linear propagation in uncompensated coherent optical systems," *Journal of Lightwave Technology*, vol. 30, no. 24, pp. 3857–3879, 2012.

[11] C. Rottondi, P. Martelli, P. Boffi, L. Barletta, and M. Tornatore, "Crosstalk-aware core and spectrum assignment in a multicore optical link with flexible grid," *IEEE Transactions on Communications*, vol. 67, no. 3, pp. 2144–2156, 2018.

[12] J. Sakaguchi, B. J. Puttnam, W. Klaus, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, K. Imamura, H. Inaba, K. Mukasa, *et al.*, "305 tb/s space division multiplexed transmission using homogeneous 19-core fiber," *Journal of Lightwave Technology*, vol. 31, no. 4, pp. 554–562, 2012.

[13] J. Wu, S. Subramaniam, and H. Hasegawa, "Efficient dynamic routing and spectrum assignment for multifiber elastic optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 11, no. 5, pp. 190–201, 2019.

[14] H. Tode and Y. Hirota, "Routing, spectrum, and core and/or mode assignment on space-division multiplexing optical networks," *Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. A99–A113, 2017.

[15] F. Arpanaei, N. Ardalani, H. Beyranvand, and S. A. Alavian, "Three-dimensional resource allocation in space division multiplexing elastic optical networks," *Journal of Optical Communications and Networking*, vol. 10, no. 12, pp. 959–974, 2018.

[16] A. Agrawal, V. Bhatia, and S. Prakash, "Core arrangement based spectrum-efficient path selection in core-continuity constrained ss-fons," in *International IFIP Conference on Optical Network Design and Modeling*, pp. 570–583, Springer, 2019.