2022 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) | 978-1-6654-7340-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/ANTS56424.2022.10227776

Enhanced Tridental Resource Assignment Algorithm for Space Division Multiplexed Elastic Optical Networks

Shrinivas Petale, Suresh Subramaniam
Department of Electrical and Computer Engineering, The George Washington University, Washington, DC, USA
{srpetale, suresh}@gwu.edu

***Abstract*—The Tridental Resource Assignment algorithm (TRA) has proven to optimally assign the resources in multicore fiber networks in the presence of intercore crosstalk (XT). It balances the trade-off between spectrum utilization and XT with the help of the tridental coefficient (TC). The TC is calculated for all the resource choices which makes it computationally expensive. In this paper, we show that we can achieve the acceptable performance of TRA while decreasing the computational overhead. We also show that by using tuned weights in TC, we can further improve the performance of TRA. We observe that acceptable performance of TRA can be achieved with 50% of the total computations and tuning minimizes the bandwidth blocking of already better performing TRA up to ≈2 orders of magnitude.**

I. Introduction

Multicore fiber (MCF) based space division multiplexed elastic optical networks (SDM-EONs) can offer a viable solution to bandwidth crunch in cloud-based services, 5G and 6G communications, high-resolution game streaming, and data center networks [1]. SDM-EON allows parallel optical signal transmission over multicore fibers (MCFs) using distance-adaptive multi-carrier transmission [2]. However, the intercore crosstalk (XT) between these parallel transmissions on weakly coupled cores degrade the quality of transmission (QoT) [3].

The intensity and effect of XT differ based on the selection of core, modulation format and the spectrum choice. The physical core geometry decides the number of adjacent cores and thus the level of XT accumulation. Selection of a core with more adjacent cores with active parallel transmissions increases the chance of higher XT accumulation. Higher modulation requires lower spectrum to carry the information however they are highly XT sensitive. On the other hand, lower modulation formats are less XT sensitive but require more spectrum. Current selection of the spectrum decides the availability of the spectrum and spectrum choices for the future connection requests due to spectrum continuity and contiguity constraints of optical communication. Non optimal selection of core, modulation format and the spectrum can also lead to fragmentation, QoT blocking, detouring, etc.

The problem of route, modulation format, core and spectrum (RMCSA) assignment is addressed in previous works [4], [5]. First the tridental resource assignment algorithm (TRA), an RMCSA algorithm, is proposed which takes into consideration the effect of selection of core, modulation format and spectrum to balance the trade-off between spectrum utilization and XT accumulations. Further an enhanced variant of TRA for transparent and translucent networks is proposed in [5]. It is shown that TRA is extremely efficient in assigning resources to balance the trade-off. TRA calculates the tridental coefficient (TC) for all the available combinations of resources. The TC is the sum of three parameters viz., capacity loss [4], spectrum utilization and location of the spectrum [5].

TRA searches through all the possible combinations of resources which leads to higher computational overhead to get optimal resources. In addition, equal weight of all the three parameters was assumed in the calculation of TC. We observed that weighing capacity loss more leads to better performance of TRA. In this paper, we first show that it is possible to save computational time with acceptable increment in the bandwidth blocking by reducing the choices of resources. We then show an approach to get the weights to improve the performance of TRA even further. TRA outperforms the baseline RMCSA algorithms and RMCSA algorithms in the literature [4], [5]. With the proposed optimizations, we see further significant improvements in the performance of TRA.

The paper is organized as follows. The network model and problem statement are introduced in Sec. II. The analysis of reducing computational complexity and weight optimization are presented in Sec. III. Sec. IV presents simulation results and the last section concludes the work.

II. Network Model and Preliminaries

We assume that every node in SDM-EON is equipped with coherent transceivers (TRXs). The flexible spectrum of C-band per core of 4 THz is considered with the granularity of 12.5 GHz [6]. Each TRX sends and receives optical signals on a carrier whose entire bandwidth occupies 37.5 GHz which is three frequency slices (FSs) [7]. The connection requests which need more spectrum than 37.5 GHz for a selected modulation form (MF) are carried by multiple TRX by forming a superchannel (SCh). Each SCh is separated from adjacent SChs using a guardband of 12.5 GHz i.e.1 FS. Each link represents a multicore fiber (MCF) on both the directions where, each MCF has identical core geometries with weakly coupled cores. Note that although the results are shown for one fiber per direction on each link, the TRA algorithms and its variants can be implemented with any number of fibers per link. Two widely accepted core geometries are considered in this paper viz., seven cores and three cores per fiber. We assume that the XT affects connections only on the neighbouring/adjacent cores and XT is negligible for other cores. In seven core MCF, each outer core has three adjacent cores and the central core has six adjacent cores. On the other hand, every core in a three-core fiber has two adjacent cores. The challenges after deploying different core geometries and corresponding XT calculations are discussed in detail in [8], [9]. No modulation and spectrum conversion is considered and spectrum continuity and spectrum contiguity are imposed. We also ensure that spatial continuity is imposed meaning same core is assigned to a lightpath on all the MCF links. Lightpath requests arrive at Poisson rate with an exponential distributed mean holding time of one (arbitrary unit). The datarate are uniformly distributed within a predefined range with a constant granularity. The definition of slice window, transmission reach model and XT aware approaches can be found at [5].

III. Improving Applied TRA

We now discuss the analysis on achieving acceptable bandwidth blocking while reducing the computational overhead. We also discuss a two-stage process to modify the TC to achieve better performance of already better performing TRA.

A. Reducing the Computational Complexity

When a connection request arrives between a source and destination nodes, TRA assigns the optimal network resource for provisioning (NRP) on the prioritized shortest path. Here, NRP is the combination of core, modulation format and the slice window (SW). It calculates tridental coefficient (TC) for each combination of NRP and choose the NRP with least TC. For a given datarate, TRA also selects only those modulation formats which offer higher XT tolerance with same spectrum requirement [5]. The general equation to calculate the number of FSs for i^{th} datarate m_i and d^{th} modulation format is given as (1). Where, n_t is the number of FSs required by TRX/carrier, δ is the spectrum width of a FS, η_d is the spectral efficiency of the d^{th} modulation format, and g_b is the number of frequency slots used as guard band. Suppose D^m is the set of such sorted modulation formats. For a datarate m, the number of NRPs on a core is shown in (2). For a datarate m, the maximum number of NRPs on a given shortest paths is shown in (3).

$$\beta_d^m = \left\lceil \frac{m_i}{(n_t\delta)\eta_d} \right\rceil \times n_t \tag{1}$$

$$N = ((S + g_b) - (\beta_d^m + g_b) + 1) = (S - \beta_d^m + 1) \tag{2}$$

$$N_{max}^m = \left(|D^m|(S+1) - \sum_{d \in D^m} \beta_d^m \right) C \tag{3}$$

The time complexity of the TRA algorithm is $O(K|D||B_d^m|LSC)$ [5]. Where, K is the number of shortest paths between every pair of nodes, D is a set of all modulation formats, B_d^m is the set of all the SWs, L is the maximum possible links per path, S is the number of FSs on a single core and C is the number of cores. The NRPs cover the time complexity of $O(|D||B_d^m|SC)$ which represent the maximum portion of the total time complexity. We can reduce the computational overhead of TRA by reducing the number of NRPs and thus speed-up the process.

B. Weighted Tridental Coefficient

The TC captures the capacity loss, spectrum requirement and the effect of fragmentation for an NRP. The details of calculation of TC is given in [5]. The NPR is represented as the combination of core c, modulation format d and SW with the index n. The TC is denoted as $\Psi(l_{\Delta(r,m)})$ and is given in (4). Here, $l_{\Delta(r,m)}$ is the incoming request with datarate m and arrived on route r. The capacity loss of the given SW in the NRP is denoted as $\psi'(l_{\Delta(r,m)}$ while $max\psi'(l_{\Delta(r,m)})$ denotes the maximum possible capacity loss in the network explained in [5]. β_d^m represents the required spectrum in the form of number of frequency slots to carry the datarate with the given baudrate of the TRX. β_1^m is the maximum number of frequency slots for the datarate which can be obtained when the lowest modulation format (d=1) is used. The third parameter in (4) refers to the normalized index of the SW where S is the total number of frequency slots in C-band.

$$\Psi(l_{\Delta(r,m)}) = \frac{\psi'(l_{\Delta(r,m)})}{max\psi'(l_{\Delta(r,m)})} + \frac{\beta_d^m}{\beta_1^m} + \frac{n}{S - \beta_d^m + 1}. \tag{4}$$

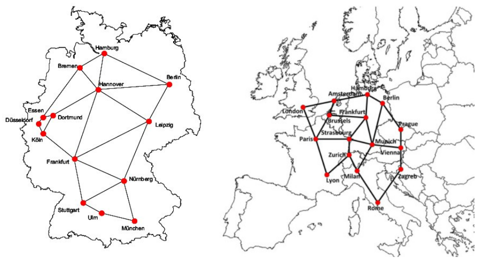
Each parameter in the TC contributes differently in improving the performance of TRA. Thus, we weighted the three parameters in (4) with α, β and $(1-\alpha-\beta)$ as shown in (5) such that $0 \le \alpha, \beta, (\alpha+\beta) \le 1$. All the results shown in [5] are obtained when the weights are 1 in (4), which is similar to α=β=$\frac{1}{3}$ in (5).

$$\Psi(l_{\Delta(r,m)}) = \alpha \times \frac{\psi'(l_{\Delta(r,m)})}{\max\psi'(l_{\Delta(r,m)})} + \beta \times \frac{\beta_d^m}{\beta_1^m} + (1-\alpha-\beta) \times \frac{n}{S - \beta_d^m + 1} \tag{5}$$

We use a two-stage method to optimize the weights, α and β, to improve the performance of TRA. In first stage, we run TRA for only 10% of the total connection requests (10k with another 1k warmup calls) for different sets of α and β. The variation in α and β leads to different TC as shown in (5) which in turn changes the network performance. In second stage, we fetch the α and β for which the observed bandwidth blocking probability (BBP) is the lowest. Finally, we run the TRA for 100k connection requests with separate 10k connections for warmup for different loads for the set of α and β.

IV. Simulation Results

We now present the results for both the analysis on TRA for variety of scenarios. We employ two topologies, as illustrated in Figure 1, namely generic German (DT) (Figure 1a) and European (EURO) (Figure 1b) [10]. Each core in an MCF has 4THz of C-band spectrum with a slice width of 12.5 GHz i.e. 320 FSs (S = 320). Connections arrive according to



(a) (b)

Figure 1: Network topologies a) DT (12 Nodes), b) EURO (16 Nodes) [10].

Poisson connection arrival process with exponential holding times of mean one time unit. In every iteration, we simulate 110,000 requests and use the first 10,000 connections to let the network reach steady state. Each experiment runs ten iterations to yield 95% confidence interval. The datarates are uniformly distributed between 40 Gbps to 400 Gbps with the granularity of 40 Gbps. Two core geometries with three cores and seven are cores are used in the network. There exist three shortest paths between each source and destination node pair which are arranged as per priority based path selection discussed in [5]. We assume five modulation formats viz. PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, and PM-64QAM. We consider two values of average XT between two adjacent cores after a single span of propagation, denoted as XT_{μ}, -40 dB and -25 dB. Transmission reach is the maximum distance which can be traversed with the selected modulation format and the status of the overlapping spectrum on the adjacent cores. The transmission reach model corresponding to the XT_{μ} when TRX is operating at 28 GBaud and span length is 50 km [7]. The desired number of NRPs are selected uniformly from the complete set of NRPs.

We first present the performance of TRA for different number choices of NRPs. Fig. 2 shows the variation of BBP with 95% confidence interval for various numbers of NRPs. The total number of NRPs in C=7 case for the datarates of 40 Gbps, 80 Gbps, …, 400 Gbps is 2226 (N^1_{max}), 2226, 4431, 4431, 4431, 6615, 6615, 6615, 6552, 6552 (N^{10}_{max}), respectively. Similarly, The total number of NRPs in C=3 case for the datarates of 40 Gbps, 80 Gbps, …, 400 Gbps is 954 (N^1_{max}), 954, 1899, 1899, 1899, 2835, 2835, 2835, 2808, 2808 (N^{10}_{max}), respectively. Given a number of NRPs that can be used, we uniformly select the NRPs from the pool of all NRPs and calculate TC for them. For every NRP, spectrum availability check, self-XT check and cross-XT check are performed before even calculating the TC (refer Definition 6.1 in [5]). As the total NRPs are different for different datarates, for a fixed number of NRPs available to use, the percentage utilization of the NRPs per datarate is different. However, we present the BBP for 100% resource availability in the last data point to represent the performance of actual TRA. We observed that the BBP doesn't significantly decrease till we use ≈50% of NRPs. In all the scenarios, we significantly reduce the computational complexity and still achieve acceptable range of BBP. We observed that the

Table I: Sets of (α, β) corresponding to lowest and highest BBP.

	Lowest BBP	**Highest BBP**
Topology, C, XT_{μ}(dB), Load(Erlang)	(α, β)	(α, β)
DT, 7, -40dB, 6000	(0.95, 0.05)	(0.45, 0.45)
DT, 3, -25dB, 800	(0.65, 0.05)	(0.05, 0.85)
EURO, 7, -40dB, 4800	(0.9, 0.05)	(0.3, 0.45)
EURO, 3, -40dB, 1800	(0.4, 0.05)	(0.05, 0.65)

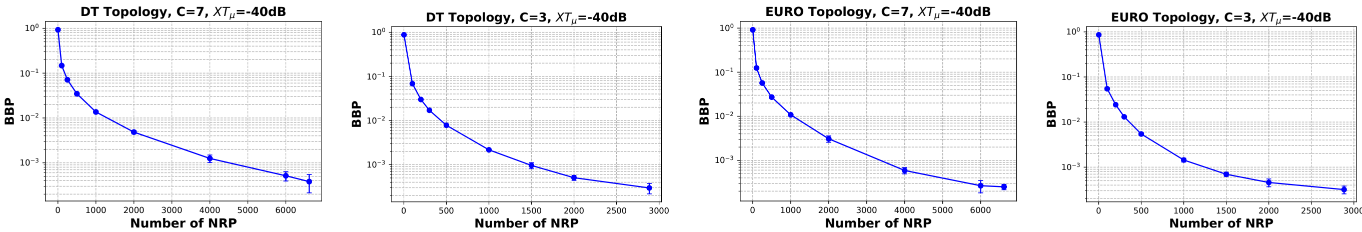
number of blocked calls doesn't change significantly but due to different datarates, we see different values of BBP. For example in case of EURO topology with C=7 case, when the NRPs are 6000 as shown in Fig. 2c, the average number of blocked connection requests are 72 while for 4000 NRPs it is 87 out of 100k connection requests. Similarly, in case of DT topology with C=7 case, when the NRPs are 6000 as shown in Fig. 2a, the average number of blocked connection requests are 48 while for 4000 NRPs it is 87 out of 100k connection requests.

After executing the two-stage process explained in Section III-B, we obtained the optimized values of α and β which leads to lowest BBP for 10% of the total connection requests. The variation of the BBP is shown as the scatter plot for various topologies, core types, XT_{μ} and load in Fig. 3. The step size is kept as 0.05. We kept the load higher to make sure that BBP is non-zero. It can clearly be seen that the performance of BBP can significantly reduces when α is large and β is small. We analyzed the variation in BBP and fetched the (α, β) for which BBP is lowest and highest, respectively. The list of such (α, β) are shown in Tab.I.

Finally, we compare the performance of TRA for different α and β for different sets of loads with 100k connections and separate 10k warmup connections as shown in Fig. 4. We compare the performance of TRA for the α and β which yield lowest BBP in second stage and highest BBP from stage one. We also compare TRA when α=β=$\frac{1}{3}$ which represent the TRA published in [4], [5] and when α=1, β=0 which represents TRA with only capacity loss. We can clearly see that although the BBP was observed for 10% of the connection arrivals, same results are obtained for 100% of the connection arrival for all the loads. In addition, it is interesting to see that even if we don't do any optimization and set α=1, we get near to optimal results which are better that TRA with α=β=$\frac{1}{3}$.

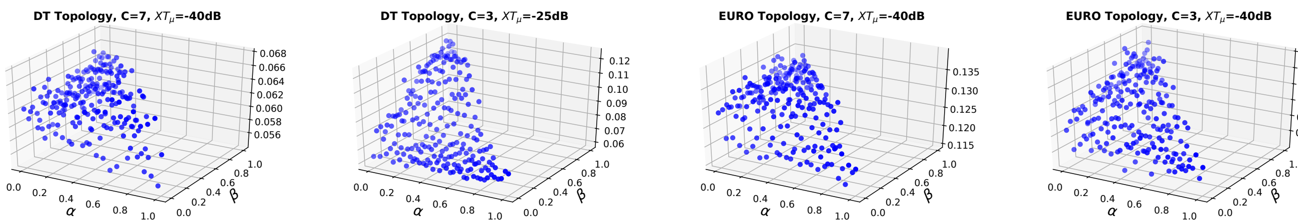
V. Conclusion

We studied the performance of proposed tridental resource assignment (TRA) algorithm which optimally selects route, modulation format, core and spectrum for assignment in multicore fiber based space division multiplexed elastic optical networks. TRA was proven to efficiently balance the trade-off between spectrum utilization and intercore crosstalk (XT) accumulations. TRA scans through all the available resources which makes it computationally expensive. In this paper, we shown that we can achieve faster convergence using limited resources with acceptable increment in the bandwidth blocking. We have also shown that by optimizing the weights of capacity loss, spectrum utilization and spectrum choice,



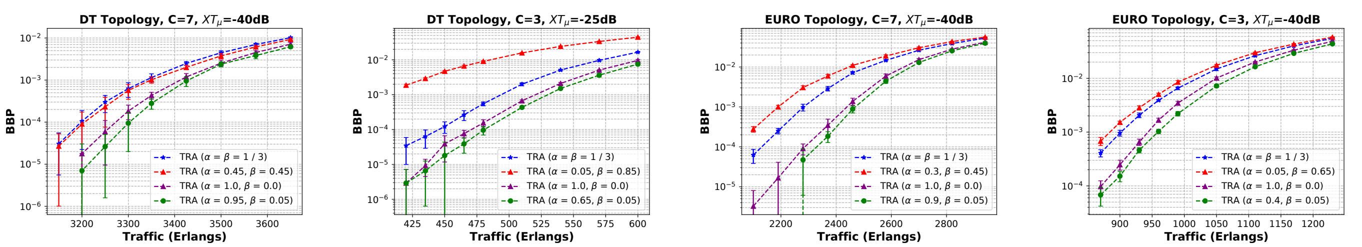
(a) (b) (c) (d)

Figure 2: Variation in BBP for limited number of NRPs for XT_{μ}=-40dB a) DT topology, C=7 and 3250 Erlang (Figure 2a), b) DT topology, C=3 and 1260 Erlang (Figure 2b), c) EURO topology, C=7 and 2160 Erlang (Figure 2c), d) EURO topology, C=3 and 840 Erlang (Figure 2d).



(a) (b) (c) (d)

Figure 3: Variation in BBP for all α and β for a) DT topology, C=7, XT_{μ}=-40dB and 6000 Erlang (Figure 3a), b) DT topology, C=3, XT_{μ}=-25dB and 800 Erlang (Figure 3b), c) EURO topology, C=7, XT_{μ}=-40dB and 4800 Erlang (Figure 3c), d) EURO topology, C=3, XT_{μ}=-40dB and 1800 Erlang (Figure 3d).



(a) (b) (c) (d)

Figure 4: Variation in BBP for different sets of α and β for a) DT topology, C=7 and XT_{μ}=-40dB (Figure 4a), b) DT topology, C=3 and XT_{μ}=-25dB (Figure 4b), c) EURO topology, C=7 and XT_{μ}=-40dB (Figure 4c), d) EURO topology, C=3 and XT_{μ}=-40dB (Figure 4d).

we can further improve the performance of TRA which was already better performing than baseline algorithms and algorithms in literature. Better performance of TRA can also be obtained by considering only capacity loss without doing weight optimization.

Acknowledgement This work was supported in part by NSF grant CNS-1813617.

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] 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.

[4] S. Petale, J. Zhao, and S. Subramaniam, "Tridental resource assignment algorithm for spectrally-spatially flexible optical networks," in *ICC 2021-2021 IEEE International Conference on Communications (ICC)*, pp. 1–7, IEEE, 2021.

[5] S. Petale, J. Zhao, and S. Subramaniam, "Tra: an efficient dynamic resource assignment algorithm for mcf-based ss-fons," *Journal of Optical Communications and Networking*, vol. 14, no. 7, pp. 511–523, 2022.

[6] 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.

[7] 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.

[8] S. Petale and S. Subramaniam, "An ml approach for crosstalk-aware modulation format selection in sdm-eons," in *2022 International Conference on Optical Network Design and Modeling (ONDM)*, pp. 1–6, IEEE, 2022.

[9] S. Petale and S. Subramaniam, "Machine learning-aided resource assignment in space division multiplexed elastic optical networks," in *Proc. International Conference on Computer Communications and Networks (ICCCN)*, 2021.

[10] R. Goścień and M. Kucharzak, "On the efficient optimization of unicast, anycast and multicast flows in survivable elastic optical networks," *Optical Switching and Networking*, vol. 31, pp. 114–126, 2019.