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Efficient and Optimized TRA Algorithm For MCF-based SDM-EONs

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***Abstract*—In the presence of intercore crosstalk (XT), the Tridental Resource Assignment (TRA) algorithm, which is a route, modulation, core, and spectrum assignment (RMCSA) algorithm, has shown to best assign resources in multicore fiber-based optical networks. In TRA, the tridental coefficient (TC) is used to balance the trade-off between spectrum utilization and XT accumulation. The TC is calculated for all resource choices to choose the optimal resource choice, which is computationally intensive. In this paper, we demonstrate a multistage optimization technique to improve the performance of TRA while cutting down the computational cost. The optimization includes a reduction in computational cost and employing customized weights in TC. We observe that at least equal performance of TRA can be attained with only 60% of the total calculations and optimized weights.**

I. INTRODUCTION

Multicore fiber (MCF)-based space division multiplexed elastic optical networks (SDM-EONs) can solve capacity issues in cloud-based services, 5G and 6G communications, high-resolution game streaming, and data centre networks. SDM-EON uses distance-adaptive multi-carrier transmission to transmit parallel optical signals across multicore fibers (MCFs). However, these parallel transmissions on weakly-coupled cores reduce the quality of transmission (QoT) due to intercore crosstalk (XT) [1].

XT accumulation depends on core geometry; more neighbouring cores with active parallel transmissions boost XT accumulation. XT-sensitive higher modulation requires lower spectrum. On the other hand, lower modulations use more spectrum but are less XT sensitive. Spectrum continuity and contiguity restrictions of optical communication determine spectrum availability for future connection demands. In other words, the combination of core, modulation, and spectrum determines the strength and impact of XT. In addition, fragmentation, QoT blocking, detouring, etc can result from non-optimal selection of core, modulation, and spectrum.

The problem of selection of core, modulation, and spectrum is referred to as route, modulation, core and spectrum (RMCSA) assignment problem and is addressed in previous works [2], [3]. The tridental resource assignment (TRA) algorithm, an RMCSA algorithm, balances spectrum utilization and XT accumulations by optimally selecting core, modulation, and spectrum. An upgraded version of TRA for transparent and translucent networks is proposed in [3]. TRA balances the trade-off between spectrum utilization and XT accumulations efficiently by calculating the tridental coefficient (TC), which is the sum of capacity loss [2], spectrum utilization and spectrum placement, for all the resource choices [3].

TRA is computationally costly because of exhaustive calculations of TC and the weights in TC are assumed equal for all three factors. This study leverage on improving these two directions. In this paper, we propose a step-wise optimization approach to decrease the processing time with tolerable bandwidth blocking and optimize the weights offline to improve the performance of TRA even further. TRA outperforms baseline and literature RMCSA algorithms [2], [3]. The enhancements boost both the speed and performance of TRA significantly.

The paper is organized as follows. The multistage optimization approach is presented in Section II. The network model and simulation results are presented in Section III and IV, respectively. The last section concludes the work.

II. MULTISTAGE OPTIMIZATION FOR APPLIED TRA

In this section, we outline a three-stage optimization to improve the speed and performance of TRA as follows. The stages, which include the analysis of bandwidth blocking, finding the amount of allowed resources and finding optimized weights, are discussed in detail as follows.

A. Reducing the Computational Complexity

TRA assigns the best resource choice (RC) to a connection request on the prioritized shortest path between source and destination. An RC is a combination of core, modulation, and slice window (SW) [3]. It calculates tridental coefficient (TC) for each RC and chooses the RC with lowest TC. For a given datarate, TRA checks the modulation with highest XT tolerance if the spectrum requirement is same for two or more modulations. The standard equation to compute FSs for i^{th} datarate m_i and d^{th} modulation is (1). Where n_t is the number of FSs required by TRX/carrier, δ is the spectrum width of an FS, η_d is the spectral efficiency of the d^{th} modulation, and g_b is the guard band frequency slots. Let D^m be such sorted modulations with highest XT tolerance for respective spectrum requirements. The number of RCs per core at datarate m are $((S+g_b)-(\beta_d^m+g_b)+1)$ which is $(S-\beta_d^m+1)$. Thus, the maximum number of RCs on shortest path for a datarate m is given by (2).

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

$$N_{max}^m = \left(|D^m|(S+1) - \sum_{d\in D^m} \beta_d^m \right) C \tag{2}$$

The time complexity of TRA algorithm is $O(K|D||B_d^m|LSC)$ [3], where K is the number of shortest paths between every pair of nodes, D is a set of all modulations, B_d^m is the set of all SWs, L is the maximum possible links per path, S is the number of FSs on a core, and C is the number of cores. The RCs cover the most time

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complexity, $O(|D||B_d^m|SC)$. Lowering RCs speeds up TRA by reducing computational overhead.

B. Choosing the Limit on Resources

As shown in (2), the number of RCs per datarate are different. Thus, we use percentage of RCs on a network level. This means that, for any datarate, out of total RCs that percent of RCs are considered for calculation of TC. When the percent RCs are reduced, the bandwidth blocking increases. However, the increase is gradual and then significantly higher. We use τ as a higher end of bandwidth blocking to select the lowest value of percent RCs. The corresponding percent RCs are then allowed to be used to make the TRA run faster and with acceptable performance.

C. Weighted Tridental Coefficient

The TC is the sum of capacity loss, spectrum requirement, and spectrum location which are weighted equally [3]. The TC is denoted as $\Psi(l\Delta(r,m))$ and is shown in (3). Each RC is a representation of core c, modulation d, and SW with index n. The request with datarate m and route r is $l_{\Delta(r,m)}$. The capacity loss of the given SW in the RC is $\psi'(l_{\Delta(r,m)}$, while $max\psi^{'}(l_{\Delta(r,m)})$ is the network's maximum capacity loss, as discussed in [3]. The transceiver's baudrate determines the number of frequency slots needed to transport the datarate. The lowest modulation (d=1) yields the most frequency slots for the datarate: β_1^m. The third parameter in (3) is the SW's normalised index, where S is the total number of slots in C-band.

$$\Psi(l_{\Delta(r,m)}) = \frac{\psi'(l_{\Delta(r,m)})}{max\psi^{'}(l_{\Delta(r,m)})} + \frac{\beta_d^m}{\beta_1^m} + \frac{n}{S-\beta_d^m+1}. \quad (3)$$

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

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

To enhance TRA, we tune α and β in two sub-stages. In the first sub-stage, we execute TRA for 10% of connection requests (10k with 1k warmup calls in this case) for different sets of α and β with a gradual increase of ϵ. In the second sub-stage, we find the α and β with the lowest observed bandwidth blocking probability (BBP).

III. NETWORK MODEL AND PRELIMINARIES

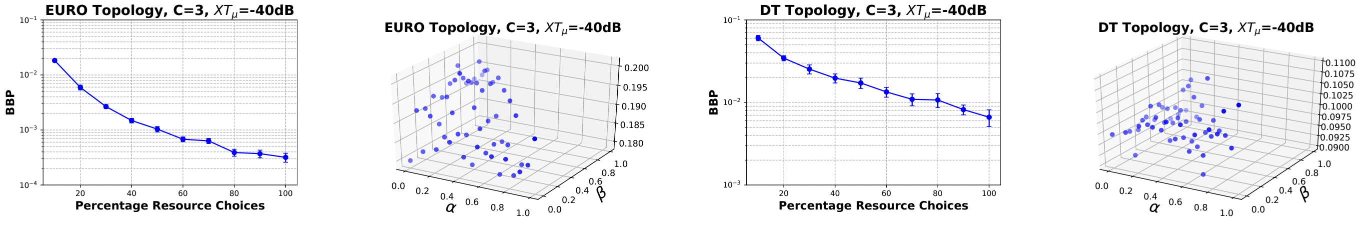
We assume every SDM-EON node has coherent transceivers (TRXs). The flexible spectrum of C-band per 4 THz core with 12.5 GHz granularity [4]. Each TRX transmits and receives optical signals on a carrier with 37.5 GHz bandwidth, three frequency slices (FSs) [5]. Multiple TRX establish a superchannel (SCh) to carry connection requests for MFs that require more spectrum than 37.5 GHz. Each SCh is separated from adjacent SChs using a guardband of 12.5 GHz i.e.1 FS. Spectrum continuity and contiguity are enforced without modulation or spectrum conversion. We enforce spatial continuity by assigning the same core to a lightpath on all MCF linkages. Lightpath connections arrive at Poisson-rate with an exponential distributed mean holding time of one (arbitrary unit). The definition of slice window, transmission reach model, and XT-aware approaches can be found at [3].

IV. SIMULATION RESULTS

We now present the results on performance of TRA and its optimized variants in variety of scenarios. We use two typologies, European (EURO) and general German (DT) [3]. MCF cores have 4 THz of C-band spectrum and 320 FSs (S = 320). Poisson connections arrive exponentially with mean one time unit holding periods. We simulate 110,000 connection requests and utilise the first 10,000 connections to establish steady state in each iteration. Ten iterations are executed to get 95% confidence intervals. The datarates are in the range of 40 Gbps to 400 Gbps with 40 Gbps granularity. We present the results for three-core fibers, however, the optimization approach is not limited by number of cores. We have observed the similar outcomes for seven-core topology, not added here due to page limitation. According to priority-based path selection in [3], each source-destination pair has three shortest paths. We use PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, and PM-64QAM. We consider the average XT between two neighbouring cores after a single span of propagation, denoted as XT_μ, of -40 dB. Transmission reach model for baudrate of 28 GBaud TRX and 50 km span length is used from [5]. The desired number of RCs for each datarate is uniformly picked from the complete set. We use ϵ=0.11 for early convergence. τ is selected as the lowest one digit bandwidth blocking with same multiplier ($\times 10^x$).

First, we evaluate the performance of TRA for different percentage of RCs. Fig.1 illustrates BBP with 95% confidence interval for different percentage of RCs. The total number of RCs in C=3 scenario with datarates of 40 Gbps, 80 Gbps, $\ldots$, 400 Gbps, is 954 (N_{max}^1), 954, 1899, 1899, 1899, 2835, 2835, 2835, 2808, 2808 (N_{max}^{10}). We compute TC for all the picked RCs that can be used. Before computing the TC, every RC undergoes spectrum availability, self-XT check, and neighbouring-XT check (definition 6.1 in [3]). In search of τ, BBP doesn't decrease significantly till we utilize 60% RCs in EURO topology and 80% RCs in DT topology. We found that the rate of increase of BBP is comparable with that of rate of increase of percent RCs since the RCs are reduced in proportion for each datarate. The average number of blocked connection requests out of 10k connection requests for 100% to 10% of RCs for 40Gbps-400Gbps in EURO topology are 18.8, 22.8, 23.6, 38.4, 41.4, 63, 90.4, 163, 368, 1169.2, and in DT topology are 42, 51.6, 66, 68, 83, 107.2, 123.8, 160, 223.6, 410.4, respectively.

After running the two-sub-stage method explained in Section II-C, we acquired the optimum values of α and β, which resulted in the lowest BBP for 10% of connection requests.

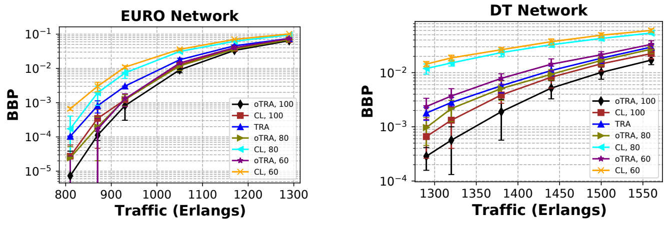


(a) (b) (c) (d)

Figure 1: Variation in BBP for limited percentage of RCs for XT_μ=-40dB and for different values of α and β for EURO topology in Fig.1a and Fig.1b, respectively, and for DT topology in Fig.1c and Fig.1d, respectively.

Table I: Sets of (α, β) corresponding to lowest BBP at C=3 and XT_μ=-40(dB).

Topology	Load(Erlang)	(α, β)	B_l	B
EURO	2000	(0.77, 0.11)	0.179394	0.192362
DT	2250	(0.66, 0.11)	0.0905354	0.0996859



(a) (b)

Figure 2: Variation in BBP of different versions of TRA for different loads for (a) EURO topology, (b) DT topology.

To maintain BBP to a non-zero value at 100% of resources, we keep the load at a higher end. The optimal values of (α, β), load, corresponding BBP, denoted as B_l, and BBP corresponding to α=β=$\frac{1}{3}$, denoted as B, are given in Tab.I. The scatter plot of BBP with respect to variation in (α, β) is shown in Fig.1b and Fig.1d for EURO and DT topologies, respectively. We observe that BBP decreases dramatically when $\alpha \geq 0.66$ and $\beta \leq 0.11$.

Finally, we examine the performance for different variants of TRA with TRA. Here, TRA represents the original version of TRA, published in [3], which is when α=β=$\frac{1}{3}$ and 100% RCs. TRA with optimal weights is denoted as oTRA and TRA with α=1.0 and β=0.0 is denoted as CL, which is the abbreviation of capacity loss algorithm. The adjacent value is the % RCs. The BBP is obtained under different loads with 100k connections and 10k warmup connections as shown in Fig. 2. It's also noteworthy that even without optimization and setting α=1, CL, we obtain near-optimal results that are better than TRA with α=β=$\frac{1}{3}$ at 100% RCs. The nearly equal performance to TRA can be obtained at the % RCs obtained in Stage 2. Thus with the offline calculations the speed of TRA increases significantly while maintaining the same or better results. In addition, the results can be optimized further by reducing ϵ to a lower value to get precise α and β, and increasing number of 10% of connections to larger value to get the more reliable variation. The time of execution per connection in TRA takes about 5-10 ms depending on the topology. The reduction in execution time is directly proportional to the reduction in RCs. For example, the execution time of oTRA at 60% RCs reduces to 59.84% and 61.76% of that of oTRA and TRA at 100% RCs, respectively in DT topology.

In future, the work can be expanded in two directions. First, machine learning (ML) can be used to replicate the strategy of selection of RCs by TRA. Second, a ML-aided standard template to optimize *any* RMCSA algorithm, similar to our previous work [6], can be used to obtain *guaranteed* improvements.

V. CONCLUSION

In multicore fiber-based space division multiplexed elastic optical networks, the tridental resource assignment (TRA) algorithm optimally assigns route, modulation, core, and spectrum. TRA effectively balances the spectrum utilization and intercore crosstalk (XT) accumulations with the help of tridental coefficient (TC) on the cost of computational overhead. This research present a multistage optimization approach to optimize TRA to achieve similar or better performance of TRA. We obtain the reduced number of resource choices and optimized weights in TC which in turn yield quicker convergence with desired bandwidth blocking. The TRA's performance, which was already better than baseline algorithms in literature, can also be improved by considering only capacity loss.

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