Nonlinear-Impairments- and Crosstalk-Aware Resource Allocation Schemes for Multicore-Fiber-based Flexgrid Networks

Nonlinear-Impairments- and Crosstalk-Aware Resource Allocation Schemes for Multicore-Fiber-based Flexgrid Networks

Madushanka Nishan Dharmaweera[(1)], Li Yan[(2)], Magnus Karlsson[(1)], Erik Agrell[(2)]

[(1)] Department of Microtechnology and Nanoscience, Photonics Laboratory, Chalmers University of Technology, Gothenburg, Sweden, nishan@chalmers.se
[(2)] Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden

Abstract *In this study, we propose a novel spectrum and core allocation scheme that incorporates both intra-core physical layer impairments and inter-core crosstalk. We demonstrate that accounting for the latter increases spectral efficiency by at least 50% when crosstalk is significant.*

Introduction

Increasing internet traffic and emerging bandwidth-intensive applications have instigated the development of flexgrid optical networks. However, their potential growth is hindered by the limited transmission capacity of single-core fibers (SCF) in optical networks. To overcome this capacity limitation and provide increased throughput, next-generation optical networks are envisioned to combine flexgrid with space-division multiplexing (multimode and multicore fiber) technologies. Multicore-fiber flexgrid (MCF-Flex) networks have thus drawn the attention of many researchers[1,3,4].

Both linear and nonlinear physical-layer impairments (PLI) that arise within a core (i.e., intra-core PLI) and between cores (i.e., inter-core crosstalk) strongly influence the performance of MCF-Flex networks. By accurately accounting for intra-core PLI, the routing and spectrum allocation (RSA) scheme presented in[2] offered spectral efficiency improvements in SCF-based flexgrid networks over existing transmission-reach-based RSA schemes. On the other hand, traffic blocking in dynamic MCF-Flex networks[3,4] was reduced by accounting for inter-core crosstalk. However, to the best of our knowledge, intra-core PLI and inter-core crosstalk have not been jointly considered in previous studies.

In this paper, we present the first novel spectrum and fiber core allocation scheme to increase the spectral efficiency of MCF-Flex networks while accurately accounting for both intra-core PLI and inter-core crosstalk.

PLI model and problem statement

The intra-core PLI can be estimated using the model in[5,6]. As inter-core crosstalk can be regarded as additive white Gaussian noise, the signal-to-noise ratio (SNR) of a subcarrier i in core z of link l can be expressed as[7],

$$\mathrm{SNR}_i = \frac{G}{G^{\mathrm{ASE}} + G^{\mathrm{NLI}}_{ilz} + G^{\mathrm{CT}}_{ilz}}. \quad (1)$$

Here G, G_{ASE}, G^{NLI}_{ilz}, and G^{CT}_{ilz} denote the power spectral density (PSD) of the signal, the amplified spontaneous emission (ASE) noise, the noise from intra-core nonlinear impairments (NLI), and the noise from inter-core crosstalk, respectively. The G^{NLI}_{ilz} entails noise due to self-channel interference (SCI) and cross-channel interference (XCI). In this study, G_{ASE} and G^{NLI}_{ilz} are estimated as defined in[2,6]. The inter-core crosstalk incurred by a subcarrier depends linearly on the amount of power induced by other subcarriers with the same frequency that are present in adjacent cores as well as the number of spans. Thus, $G^{\mathrm{CT}}_{ilz} = \upsilon N_l G |A_{ilz}|$ where A_{ilz} is the set of subcarriers with the exact center frequency of subcarrier i, found in adjacent cores of z of link l; υ denotes the mean crosstalk between adjacent cores per span; and N_l denotes the number of spans in link l. Depending on the properties of the fabricated fiber, υ could take on values between -65dB and -25dB[7].

Now, given a network with set of nodes V and set of links E (all $l \in E$ have two uni-directional multicore fibers in opposite directions); F, a set of cores in each fiber; C, the spectral width of each subcarrier; k, the spectral efficiency of the available modulation format; S, the number of subcarriers in every core; T, the set of connections in the network; Λ_a, the requested data rate of connection $a \in T$; G, the PSD for every $a \in T$; $\mathrm{SNR}_{\mathrm{th}}$, the required SNR threshold of the modulation format; and υ, the mean crosstalk between adjacent cores, our proposed schemes seek to allocate spectrum and cores to maximize spectral efficiency.

Based on Λ_a, k, and C, the number of subcarriers required by every connection $a \in T$ is predetermined and listed in set s_a. For example, if 4 subcarriers are needed to accommodate the data rate of a, then $s_a = \{a^1, a^2, a^3, a^4\}$ where a^j is the j^{th} subcarrier of connection a. Set D contains the subcarriers of all connections $\{a, b\} \in T$ ($D = \{a^1, .., a^4, b^1, .., b^4\}$). The spectrum (i.e., frequency) and a fiber core will be assigned to each subcarrier $i \in D$ using the proposed schemes. To reduce the complexity of the formulation, each subcarrier $i \in D$ is independently (i.e., without forming superchannels) routed along the respective shortest routing path r_i. Also, core switching is not allowed in this study.

In comparison to previous work[2,6], in this study, the degrees of freedom (DOF) arising from the availability of multiple routing paths, modulation formats, and Gs were removed. The DOF due to the availability of multiple *cores* were included instead. Additionally, the proposed schemes account for crosstalk in the noise calculation and spectrum and core allocation is performed on individual subcarriers, not individual connections.

ILP formulation

To achieve our objective, we propose an integer linear programming (ILP) solution and a simple heuristic. The proposed ILP is a modified version of our previous ILP[2]. The proposed ILP (which due to lack of space is not written in full mathematical detail) maximizes spectral efficiency by minimizing the total number of subcarriers used in any fiber core, while accounting for several constraints: A subcarrier has to guarantee the spectrum continuity constraint; two subcarriers cannot use the same spectrum in the same core of a link (non-overlapping spectrum allocation); a subcarrier has to be routed along the same core of every link along the predefined routing path (no core switching); a subcarrier is impaired not only by SCI but also by XCI induced by other subarriers in the same core; the XCI incurred by a subcarrier is related to the frequency spacing between the subcarrier and neighbouring subcarriers of the same core; a subcarier incurs crosstalk if the same spectrum is used in an adjacent core; and the total impairments incurred by a subcarrier have to be smaller than G/SNR_{th}.

Proposed heuristic

As the complexity of the proposed ILP scales poorly with the size of the network, we propose the following heuristic illustrated in Algorithm 1. First, subcarriers in D are sorted in descending order of their transmission distance. Spectrum (f_i) and core (c_i) allocation are then performed on each $i \in D$ in sequence. The function Γ returns *pass* and n_{max} (the maximum noise incurred by any subcarrier) if every subcarrier in the current network satisfies the SNR requirement, else, return *fail*. Guard bands (GBs) are provisioned between adjacent subcarriers to counter the effect of intra-core PLI. To overcome the drawbacks of fixed-size guard GBs (as shown in[2]), the size of the GB Φ and the fraction of subcarriers assigned with GBs M ($M \leq 1$) are gradually increased. Initially, we set $\Phi = 0$, $M = 1$, $\delta = 0$ (the maximum impairments incurred by any subcarrier), and $\alpha = 2$ (a weight coefficient). The variable g_i takes the value Φ if i is followed by a GB; else, 0.

Algorithm 1 Spectrum and core allocation

Inputs: $V, E, F, C, k, S, \text{SNR}_{\text{th}}, D, \Phi, M, \alpha, \delta, r_i, g_i = 0$
Outputs : spectrum occupancy in all cores

1: **for** $\forall i \in D$ (sorted order), let $\delta = 0, \{f_i, c_i\} = \infty$ **do**
2: **If** i is in the first M^{th} fraction of D **then** $g_i = \Phi$
3: **else** $g_i = 0$
4: **for** each starting subcarrier index $1 < s' < S$ **do**
5: **for** every core $z \in F$, let $t_i^{\text{PLI}} = 0$ **do**
6: **for** each link along r_i **do**
7: $t_i^{\text{PLI}} = \begin{cases} t_i^{\text{PLI}} + \infty, \text{if } s' \text{ to } s' + g_i \text{ are unavailable} \\ t_i^{\text{PLI}} + G^{\text{ASE}} + G^{\text{NLI}}_{ilz} + G^{\text{CT}}_{ilz} \end{cases}$
8: **if** $t_i^{\text{PLI}} <= G/\text{SNR}_{\text{th}}$ and $s' \leq f_i + \alpha\delta$ **then**
9: set the state of subcarrier s' as unavailable on
10: core z of links $l \in r_i$, update the network
11: call function Γ
12: **if** Γ returns *pass* & $s' + \alpha n_{\text{max}} \leq f_i + \alpha\delta_i$ **then**
13: $f_i \leftarrow s'$, $c_i \leftarrow z$, $\delta \leftarrow n_{\text{max}}$
14: set the state of subcarrier s' as available on
15: core z of links $l \in r_i$, update the network
16: **if** $f_i \neq \infty$ (a feasible subcarrier is found) **then**
17: Set state of subcarriers f_i to $f_i + g_i$ as occupied on
18: core c_i of links $l \in r_i$, update the network
19: **else if** $M \leq 1$ **then**
20: increase M by 0.25 ; **re-set** and **begin** from line 1
21: **else**
22: Increase GB by 1, M = 0.25 ; **re-set** and **begin** from line 1

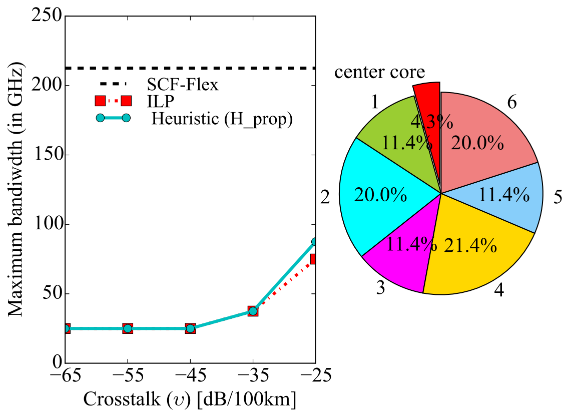

Fig. 1: Bandwidth vs. υ and percentage core usage when $\upsilon \geq -45$dB for 6-node chain network.

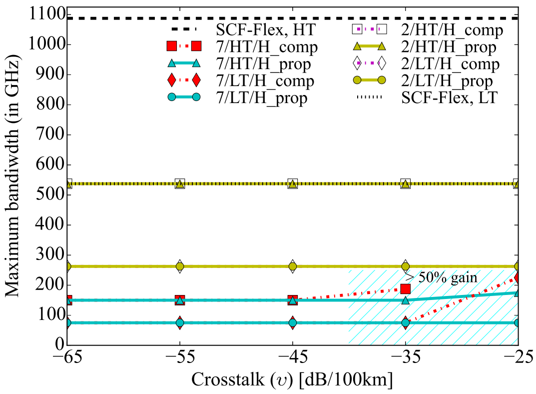

Fig. 2: Bandwidth vs. υ for DT network

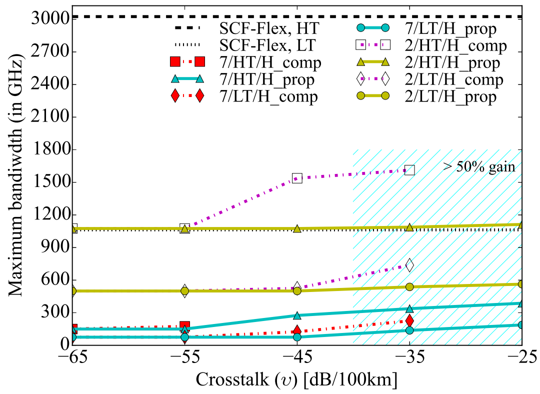

Fig. 3: Bandwidth vs. υ for sDT network

Performance evaluation

Simulations were performed using a 2-core and a 7-core fiber on a small 6-node chain network (avg. link length 660 km), the real-size 14-node Deutsche Telekom (DT) network (avg. link length 170 km), and a scaled DT (sDT) network (avg. link length 800 km)[8]. The network traffic volume was varied by assigning a 100 Gbps (LT) or 200 Gbps (HT) bit rate to every connection. Connections were modulated using the PM-QPSK scheme ($k = 4$ bit/s/Hz), and SNR_{th} was set to achieve a bit error rate[6] of 4×10^{-3} . While $G = 10$ mW/THz, the inputs C and S are 12.5 GHz and 300 subcarriers, respectively. The relevant transmission parameters of the fibers were adopted from[2]. Considering the geometry of the fiber, each core is assumed to experience crosstalk from the adjacent 3 cores, while the center core of the 7-core fiber is affected by 6 outer cores. The results of the proposed scheme (H_prop) for different crosstalk values are compared against the results of an SCF-Flex network and the work of[2] that was modified by including additional DOF due to multiple cores (H_comp).

From the comparison in Fig. 1, it is evident that the heuristic offers comparable results to that of the ILP. Also, results show that center core is sparsely used at high υ values. In Figs. 1–3, it is observed that the achievable spectral efficiency gains with H_prop for the 7-core fiber diminishes as υ increases. As the amount of crosstalk is dependent on the number of adjacent cores, the results for the 2-core fiber show more tolerance to variations in υ. As crosstalk is linearly dependent on the number of spans and intra-core PLI (more specifically, XCI) is dependent on the number of neighbouring channels, performance degradation of the 7-core fiber is more obvious in Fig. 3 (sDT network) and at HT traffic volumes. Nevertheless, in a 7-core fiber, each core carriers a reduced number of slots and thus experiences less XCI than both the SCF and 2-core fiber. Therefore, at HT, the 7-core fiber provides significant spectral gains over SCF even at high υ. From Figs. 2 and 3, it is also clear that H_comp performs worse (consumes $\geq$ 50% more bandwidth) than H_prop and becomes infeasible at very high υ values. This phenomenon is magnified in the sDT network, at HT, and for the 7-core fiber. H_comp performs worse due to the fact that at the spectrum and core allocation stage, it is oblivious to actual crosstalk noise and, therefore, uses a higher number of GBs to compensate for this additional noise.

Conclusion

The proposed spectrum and core allocation scheme increases spectral efficiency of an MCF-Flex network by accurately accounting for intra-core PLI and inter-core crosstalk while alleviating the drawbacks of fixed-size GB assignment. When inter-core crosstalk is severe, the proposed scheme achieves more than a 50% increase in spectral efficiency over schemes that only account for intra-core PLI.

References

[1] D. Klonidis et al., “Spectrally and spatially flexible optical network planning and operations,” IEEE Commun. Mag., vol. 53, no. 2, pp. 69–78, 2015.

[2] J. Zhao et al.,“Nonlinear impairment-aware static resource allocation in elastic optical networks,” JLT, vol. 33, no. 22, pp. 4554–4564, 2015.

[3] A. Muhammad et al., “Resource allocation for space-division multiplexing: Optical white box versus optical black box networking,” JLT, vol. 33, no. 23, pp. 4928–4941, 2015.

[4] S. Fujii et al., “On-demand spectrum and core allocation for multi-core fibers in elastic optical network,” JOCN, vol. 6, no. 12, pp. 1059–1071, 2014.

[5] P. Johannisson and E. Agrell, “Modeling of nonlinear signal distortion in fiber-optical networks,” JLT, vol. 32, no. 23, pp. 4544–4552, 2014.

[6] L. Yan et al., “Resource allocation for flexible-grid optical network with nonlinear channel model,” IEEE JOCN, vol. 7, no. 11, pp. B101–B108, 2015.

[7] T. Hayashi et al., “Uncoupled multi-core fiber enhancing signal-to-noise ratio,” Optics Express, vol. 20, no. 26, pp. B94–103, 2012.

[8] R. Hulsermann et al., “A set of typical transport network scenarios for network modelling,” 5th ITG Workshop on Photonic Networks, pp. 65–71, 2004.