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

This document has been downloaded from Chalmers Publication Library (CPL). It is the author’s version of a work that was accepted for publication in:

ECOC 2016; 42nd European Conference on Optical Communication; Proceedings of

Citation for the published paper:

Downloaded from: http://publications.lib.chalmers.se/publication/247087

Notice: Changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published source. Please note that access to the published version might require a subscription.

Chalmers Publication Library (CPL) offers the possibility of retrieving research publications produced at Chalmers University of Technology. It covers all types of publications: articles, dissertations, licentiate theses, masters theses, conference papers, reports etc. Since 2006 it is the official tool for Chalmers official publication statistics. To ensure that Chalmers research results are disseminated as widely as possible, an Open Access Policy has been adopted. The CPL service is administrated and maintained by Chalmers Library.
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.

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 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 was reduced by accounting for inter-core crosstalk. However, 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. As inter-core crosstalk can be regarded as additive white Gaussian noise, the signal-to-noise ratio (SNR) of a subcarrier in core $z$ of link $l$ can be expressed as

$$\text{SNR}_i = \frac{G}{G_{\text{ASE}} + G_{\text{NLI}} + G_{\text{CT}}}.$$  (1)

Here $G$, $G_{\text{ASE}}$, $G_{\text{NLI}}$, and $G_{\text{CT}}$ 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 $G_{\text{NLI}}$ entails noise due to self-channel interference (SCI) and cross-channel interference (XCI). In this study, $G_{\text{ASE}}$ and $G_{\text{NLI}}$ are estimated as defined in. 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, $G_{\text{CT}} = v N_l G |A_{ilz}|$ where $A_{ilz}$ is the set of subcarriers with the exact center frequency of subcarrier $i$, found in adjacent cores of $z$ of link $l$; $v$ 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, $v$ could take on values between $-65$dB and $-25$dB.

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; $C_l$, 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; $\Lambda_a$, the requested data rate of connection $a \in T$; $G$, the PSD for every $a \in T$; $\text{SNR}_{\text{th}}$, the required SNR threshold of the modulation format; and $\nu$, the mean crosstalk between adjacent cores, our proposed schemes seek to allocate spectrum and cores to maximize spectral efficiency.
Based on $\Lambda_{s}$, $k$, 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 $\{(a, b) \in T$ $(D = \{a^1, \ldots, a^4, b^1, \ldots, b^4\})\}$. 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\textsuperscript{2,6}, in this study, the degrees of freedom (DOF) arising from the availability of multiple routing paths, modulation formats, and $G$s 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\textsuperscript{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 subcarriers 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 subcarrier 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 $\Gamma$ returns pass and $r_{\max}$ (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 $\Phi$ 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 $\Phi$ if $i$ is followed by a GB; else, 0.

**Algorithm 1 Spectrum and core allocation**

```
inputs: $V$, $E$, $C$, $k$, $S$, $SNR_{th}$, $D$, $\Phi$, $M$, $\alpha$, $\delta$, $r_i$, $g_i = 0$
outputs: spectrum occupancy in all cores
1: for $\forall i \in D$ (sorted order), let $\delta = 0$, $(f_i, c_i) = \infty$
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 $f^PLI_z = 0$
6: for each link along $r_i$ do
7: $t^PLI_{i} = \sum_{j} f^PLI_{i} \cdot (\text{if } s' \text{ to } s'' + g_i \text{ are unavailable})$
8: if $t^PLI_{i} < G/SNR_{th}$ and $s' \leq f_i + \alpha s''$ then
9: set the state of subcarrier $s'$ as unavailable on core $z$ of links $l \in r_i$, update the network
10: call function $\Gamma$
11: if $\Gamma$ returns pass and $s' + \alpha r_{\max} \leq f_i + \alpha s''$ then
12: $f_i \leftarrow s'$, $c_i \leftarrow z$, $\delta \leftarrow r_{\max}$
13: set the state of subcarrier $s'$ as available on core $z$ of links $l \in r_i$, update the network
14: if $f_i = \infty$ (a feasible subcarrier is found) then
15: Set state of subcarriers $f_i$ to $f_i + g_i$, as occupied on core $c_i$ of links $l \in r_i$, update the network
16: else if $M \leq 1$ then
17: increase $M$ by 0.25 ; re-set and begin from line 1
18: else
19: Increase GB by 1, $M = 0.25$ ; re-set and begin from line 1
```

![Fig. 1: Bandwidth vs. $\nu$ and percentage core usage when $\nu \geq -45$dB for 6-node chain network.](image-url)
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). 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 of \( 4 \times 10^{-3} \). 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 \( \mathrm{H}_{\text{prop}} \) 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 \( \mathrm{H}_{\text{comp}} \).

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 \( \upsilon \) values. In Figs. 1–3, it is observed that the achievable spectral efficiency gains with \( \mathrm{H}_{\text{prop}} \) for the 7-core fiber diminishes as \( \upsilon \) 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 \( \upsilon \). 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 carries 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 \( \upsilon \). From Figs. 2 and 3, it is also clear that \( \mathrm{H}_{\text{comp}} \) performs worse (consumes \( \geq 50\% \) more bandwidth) than \( \mathrm{H}_{\text{prop}} \), and becomes infeasible at very high \( \upsilon \) values. This phenomenon is magnified in the sDT network, at HT, and for the 7-core fiber. \( \mathrm{H}_{\text{comp}} \) 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