Modulation Format, Core and Spectrum Assignment in a Multicore Optical Link with and without MIMO Receivers

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ABSTRACT
We study the modulation format, core and spectrum assignment problem in a multi-core flexi-grid optical link, under the assumption that MIMO receivers can operate on various core subsets and considering distance-adaptive reaches for different modulation formats. We show results obtained following an optimization approach, comparing scenarios with and without the use of MIMO transmission.
Keywords: multicore fiber; MIMO receivers;

1. INTRODUCTION

Multicore Fibers (MCFs) are one of the main enabling technologies for Spatial Division Multiplexing (SDM) in flexi-grid optical networks [1], which can potentially lead to scale the capacity of backbone optical networks by a factor equal to the number of cores available within the fiber cladding. Unfortunately, transmission impairments introduced by inter-core crosstalk may limit such capacity scaling. Therefore, multiple-input and multiple-output (MIMO) digital signal processing transmission techniques have been proposed to eliminate the interference caused by inter-core crosstalk [2]. Typically, MIMO transmission is applied in spatial joint switching scenarios, i.e., MIMO spans all the fiber cores, which are managed and switched as a single entity. However, since MIMO complexity exhibits quadratic dependency on the number of involved cores, such approach may be not scalable to many cores. Therefore, we propose the adoption of MIMO transmission in subsets of adjacent cores within a multicore fiber and we focus on the modulation format, core and spectrum assignment to serve a set of traffic request on a single multicore link. We formulate an integer linear program (ILP) to optimally solve the problem and compare results to those obtained without the adoption of MIMO transmission.
The paper is organized as follows: Sec. 2 discusses the adopted link, transceiver and flexi-grid model. Sec. 3 details the ILP formulation. Sec. 4 provides preliminary results and Sec. 5 discusses future extensions.

2. TRANSMISSION SYSTEM AND FLEXI-GRID MODEL

2.1 Link Model

The optical network is composed of nodes connected by periodically amplified links based on multi-core fibers (MCF). The adopted MCF is the 12-core fiber described in [3]. In all links we assume the span length to be 80 km and the lumped optical amplification set to recover exactly the span loss. Noise figure Φ of the optical amplifiers is 6 dB. Propagation over these links is modeled considering ASE noise accumulation, generation of non-linear interference (NLI) and crosstalk from *nearest* cores. The ASE noise is generated by each optical amplifier and propagated to the end of the link. The ASE noise power at the output of each amplifier, evaluated on a bandwidth equal to the symbol rate R_s of the transmitted signal, is $P_{ASE} = \Phi h\nu(\theta - 1)R_S$, where θ is the amplifier gain, v is the center propagation frequency and h is the Plank's constant. The level of non-linear interference (NLI) is evaluated using the GN-model [4], applied on each core independently from the others, as the non-linear effect is generated by the interaction of channels in the same core. In order to have fast but reliable results we resort to the closed-form analytical expression for NLI, assuming incoherent accumulation along the link. Based on this approach, we consider all channels in the core under study as equally spaced and this defines a worst-case with respect to the actual condition under analysis. The last physical impairment considered is the crosstalk from *nearest* cores. This crosstalk appears only in case of presence in adjacent cores of a spectrally overlapping channel: we weight the amount of generated crosstalk on the basis of the number of overlapped spectral slots.
Thus, the evaluation of the Quality of Transmission (QoT), defined as a generalized SNR (GSNR), is obtained at any distance and given by:

$$GSNR = \frac{P_S}{P_{ASE} + \eta_{NLI} P_S^3 + \gamma_{XT} P_S}$$

where P_S is the signal power per channel launched in a link: this power is assumed to be the same for all channels in a core and also across all cores, along the same link. The optimal value of P_S is almost independent of distance and spectral load. For the link considered in this analysis, we fixed its value to -1 dBm, which is very close to the optimum for all analysed scenarios.

2.2 MIMO transmission

To reduce the impact of inter-core crosstalk, we resort to MIMO transmission. i.e., the propagation over adjacent cores and in the same frequency slots. Signals form adjacent cores are detected with synchronized coherent receivers and jointly processed to recover the transmitted information. To limit the complexity of the MIMO processing, we consider only cases when only subsets of two or three cores are jointly detected. In Fig. 1 we show the possible subsets of nearest neighbour cores considered for the case of 2 and 3 joint core. We assume an ideal behaviour of the MIMO receiver, i.e., all crosstalk generated between cores included in the MIMO processing is assumed to be fully cancelled by the equalizer.

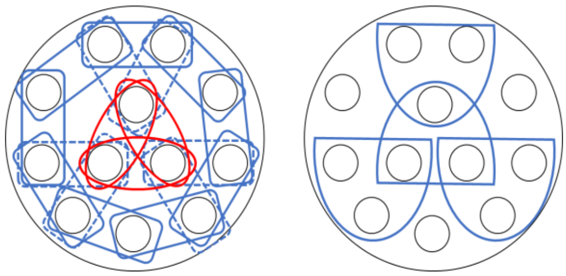

Figure 1.The considered core groups, with cardinality 2 (left) and 3 (right).

2.3 Flexi-grid model

We assume that the spectrum is flexi-grid with slot width ψ. The available spectrum portion on every core is $\Psi=P\psi$ (with P integer). The optical bandwidth occupied by a transceiver is $\Omega=S\psi$ (with S integer). If a traffic request exceeds the capacity of a single transceiver, it can be served by $\beta>1$ adjacent transceivers forming a super-channel, which is handled as a single entity, given that it is separated from the adjacent super-channels by a guard-band $G=M\psi$ (with M a small integer). In the case of MIMO transmission, the super-channel can involve multiple neighbour cores, named *group*. Transceivers support different modulation formats (i.e. DP-QPSK and DP-*n*-QAM, with n=8, 16, 32, 64). For each modulation format, we set the minimum required SNR based on the assumption of using an FEC with 28% overhead and a BER threshold of $3.8\cdot10^{-3}$, taking into account an implementation penalty of 2 dB. When considering the propagation, a channel is in service if its GSNR is above the required SNR.

3. INTEGER LINEAR PROGRAM FORMULATION

We formulate as an integer linear program (ILP) the following problem: given a set of traffic requests on a multicore optical link of predefined length, assign to every traffic request a number of transceivers, a modulation format and a spectrum portion over a group of adjacent cores to allocate such transceiver. Tab. 1 reports the sets and parameters used in the ILP formulation, whereas Tab. 2 lists the model variables. Note that the spectrum channels in set L are defined as follows: channel l_1 ranges from slot 1 to slot S, channel l_2 ranges from slot 2 to slot $S+1$ etc., so that $|L|=P-S+1$.
Moreover, the elements of set J range from 0 to $S\cdot\alpha$, where α is the maximum number of neighbours a core may have, which depends on the characteristics of the multicore fiber being considered (in our case, $\alpha=4$). Finally, in absence of MIMO receivers, the groups included in set D consist exclusively on one core, whereas with MIMO receivers groups may include 1, 2 or 3 cores, as reported in Fig.1.
Model equations are summarized in Tab.3. The objective in eq.(1) is the minimization of the rightmost occupied spectrum channel over any core. Constraints include modulation format assignment in eq.(2)-(3), core and spectrum assignment ensuring contiguity of channels belonging to the same super-channel and guard-band placement (eq. (4)-(11)) and crosstalk limitations (eq. (12)-(17)).

Table 1. Model sets and parameters

Set description	**Symbol**	**Parameter description**	**Symbol**
Set of cores	$C=\{c_1,\dots,c_{\vert C\vert}\}$	Capacity of transceiver adopting modulation format m in M	R_m
Set of modulation formats	$M=\{m_1,\dots,m_{\vert M\vert}\}$	Traffic volume of request t in T	V_t
Set of traffic requests	$T=\{t_1,\dots,t_{\vert T\vert}\}$	Minimum OSNR required by modulation format m in M	O_m
Set of cardinalities of neighbour slots	$J=\{j_1,\dots,j_{\vert J\vert}\}$	Binary, set to 1 if core m in C and c' in C are adjacent	$A_{cc'}$
Set of spectrum channels	$L=\{l_1,\dots,l_{\vert L\vert}\}$	OSNR at receiver when j in J slots are lit in neighbour cores and l in L channels are occupied in the same core	K_{jl}
Set of core groups	$D=\{d_1,\dots,d_{\vert D\vert}\}$	Binary, set to 1 if core c in C belongs to group d in D	N_{cd}
		Big constant, greater than $\vert L\vert$	Q
		Transceiver bandwidth (in slots)	F
		Guard-band width (in slots)	G

Table 2. Model variables

Symbol	Description	Type
b_{mt}	Indicates if modulation format *m* in *M* is used to transmit request *t* in *T*	binary
x_{clt}	Indicates if a transceiver allocated in channel *l* in *L* of core *c in C* serves request *t* in *T*	binary
f_{lt}	Indicates if channel *l* in *L* is the rightmost channel serving request *t* in *T*	binary
w_{dt}	Indicates if request *t* in *T* is allocated in core group *d* in *D*	binary
h_{jlt}	Indicates if any transceiver serving request *t* in *T* experiences the OSNR obtained with at most *j* in *J* neighbour lit slots and *l* in *L* co-propagating channels	binary
z_t	Maximum amount of lit slots in neighbour cores experienced by any transceiver serving request *t* in *T*	integer
y_t	Maximum amount of co-propagating channels in any core experienced by any transceiver serving request *t* in *T*	integer
p	Rightmost occupied slot	integer

Table 3. Model equations

Objective function	$min\ p$	(1)
Each traffic request is transmitted using only one modulation format	$\sum_{m\in M} b_{mt} = 1\ \forall t\in T$	(2)
Traffic volume of request *t* must not exceed the total capacity of transceivers serving request *t*	$V_t b_{mt} \leq \sum_{c\in C, l\in L} x_{clt} R_m\ \forall m\in M, t\in T$	(3)
Transceiver optical channels cannot overlap	$\sum_{i=0}^{F-1}\sum_{t\in T} x_{c,l+i,t} \leq 1\ \forall c\in C, l\in L$	(4)
Guard-bands between spectrally adjacent super-channels must be imposed	$f_{lt} + \sum_{i=0}^{G-1}\sum_{t'\in T: t'\neq t} x_{c,l+i,t'} \leq 1 + Q\left(1 - \sum_{d\in D} w_{dt} N_{cd}\right)$ $\forall c\in C, l\in L, t\in T$	(5)
Transceivers serving request *t* can be allocated only in cores belonging to the core group associated with request *t*	$Q\sum_{d\in D} w_{dt} N_{cd} \geq \sum_{l\in L} x_{clt}\ \forall c\in C, t\in T$	(6)
Each traffic request must be allocated in one core group	$\sum_{d\in D} w_{dt} = 1\ \forall t\in T$	(7)
Each (super)channel serving a traffic request must have one rightmost frequency	$\sum_{l\in L} f_{lt} = 1\ \forall t\in T$	(8)
Variable *p* must exceed the rightmost channel of every super-channel	$f_{lt} l \leq p\ \forall l\in L, t\in T$	(9)
Transceivers serving the same traffic request must be spectrally contiguous	$f_{lt} + x_{clt} \geq x_{c,l-F,t}\ \forall c\in C, l\in L: l > F, t\in T$	(10)
Spectrum allocation of transceivers serving request *t* cannot exceed the super-channel rightmost frequency	$x_{clt} l \leq \sum_{l'\in L} f_{l't} l'\ \forall c\in C, l\in L, t\in T$	(11)
Variable y_t must exceed the maximum amount of co-propagating channels in any core belonging to the core group associated with request *t*	$\sum_{l\in L, t'\in T: t'\neq t} x_{clt'} \leq y_t + Q\left(1 - \sum_{d\in D} w_{dt} N_{cd}\right)$ $\forall c\in C, t\in T$	(12)
Variable z_t must exceed the maximum amount of lit slots in neighbour cores (except those belonging to the core group associated with request t) within the optical channel of any transceiver serving request *t*	$z_t + Q(1 - x_{clt}) \geq \sum_{i=-F+1}^{F-1}\sum_{t'\in T: t'\neq t}\sum_{c'\in C: c'\neq c} x_{c',l+i,t'}(F - \lvert i\rvert)A'_{cc}$ $\forall c\in C, l\in L, t\in T$	(13)
The OSNR level of request *t* is set according to the highest spectrum load and number of neighbour lit slots experienced by any transceiver serving request *t*	$z_t \leq \sum_{j\in J, l\in L} h_{jlt} j\ \forall t\in T$ $\qquad y_t \leq \sum_{j\in J, l\in L} h_{jlt} l\ \forall t\in T$	(14) (15)
Each traffic request must be associated with one OSNR level	$\sum_{j\in J, l\in L} h_{jlt} = 1\ \forall t\in T$	(16)
The OSNR level associated with request t must exceed the OSNR threshold of the modulation format used to serve request t	$\sum_{j\in J, l\in L} h_{jlt} K_{jl} \geq \sum_{m\in M} b_{mt} O_m\ \forall t\in T$	(17)

4. RESULTS

We assume ψ=12.5 GHz and S=3, i.e., transceivers operate at 32 GBd and require an optical bandwidth Ω=37.5 GHz. The guard-band width is set to M=1, i.e., G=12.5 GHz. Due to the limited scalability of the ILP formulation, we set P=100, i.e., we consider a reduced spectrum bandwidth Ψ=1.25 THz. We consider a variable amount of traffic requests of V_t=1 Tbps and focus on three different link lengths, i.e., 400, 800 and 1600 km.

Fig. 2a plots the value of p (i.e., the rightmost occupied slot) for different values of $|V_t|$ (i.e., the number of traffic requests to be allocated), with or without MIMO transmission. Results show that MIMO transmission enables a reduction of the spectrum occupation in most of the considered traffic scenarios (on average roughly 7,2%, 8,6% and 14%, respectively for 400, 800 and 1600 km link length), enabling up to 150 GHz spectrum savings per core. Figg. 2c) and 2d) report the percentage of transceivers operating at each modulation format in a 1600 km link vs the number of requests, without and with MIMO transmission respectively. The 16QAM is used only for low values of $|V_t|$, due to the high OSNR level requirements (both inter-core or for co-propagating channels in the same core). Conversely, the OSNR requirements of QPSK tolerate full spectrum occupation in every core and QPSK is therefore preferred in most traffic configurations. When MIMO transmission is adopted, the usage of MIMO groups of 2 and 3 cores becomes advantageous, especially at low traffic loads (see Fig. 2b).

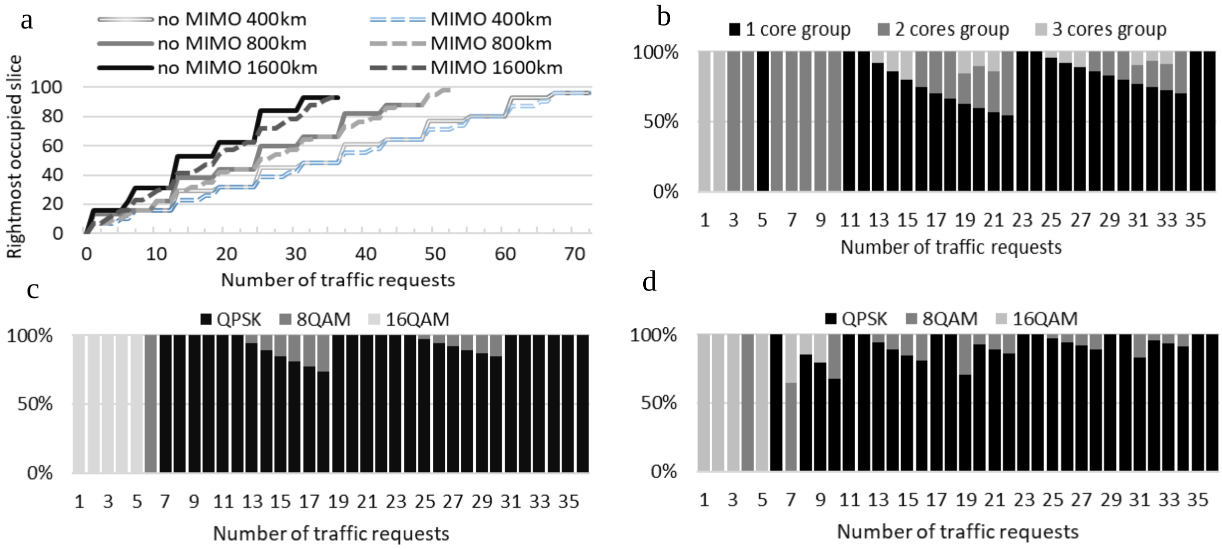

Figure 2. a) Rightmost occupied slice for different link lengths with and without MIMO transmission; b) number of used cores for MIMO; c) and d) modulation formats in a 1600 km link respectively without and with MIMO .

5. CONCLUSIONS

We discuss the benefit of MIMO transmission in a multicore fiber. The introduced optimal ILP model was used to analyse the performance of a single optical link. MIMO transmission provides increasing performance benefits for increasing link lengths, by reducing spectrum occupancy and enabling the use of more efficient modulation formats.

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