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Coupled vs Uncoupled SDM Solutions: A Physical Layer Aware Networking Comparison

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ABSTRACT

Spatial division multiplexing (SDM) is a possible solution to face the growth of data traffic. We compare performances of two SDM implementations: uncoupled fiber ribbons (UFR) and coupled-core multicore fibers (SCMCF). Respect to UFRs, SCMCFs mitigates nonlinear interference (NLI), but signals must be added/dropped simultaneously on/from all cores. In literature, mitigation of NLI in SCMCFs is investigated in point-to-point scenarios, while networking investigations are focused on switching issues. Exploiting the statistical network assessment process, we compare the two solutions jointly analyzing propagation and switching issues in scenarios with SDM cardinality of three, showing that UFRs enable larger traffic load.

Keywords: Transparent elastic optical network, Multicore fibers, Space Division Multiplexing (SDM), wavelength division multiplexing (WDM) networks, physical layer aware networking, strongly coupled multicore fibers.

1. INTRODUCTION

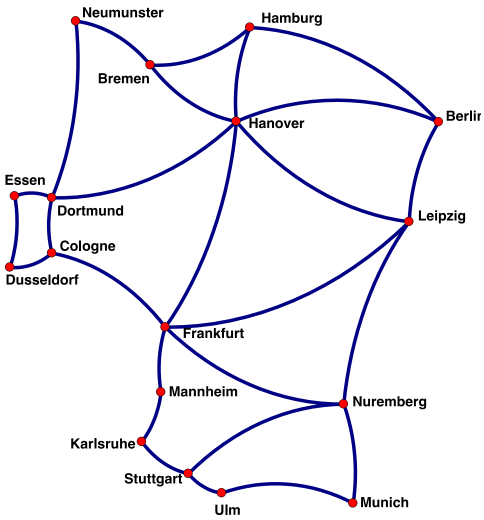

Fig. 1. The analyzed German network topology.

Spatial division multiplexing (SDM) is the most feasible and seamless solution to face the growth of traffic demand in optical transport networks [1,2] by deploying the total available bandwidth multiplied by the SDM cardinality. Among the available solutions to implement the SDM paradigm [3] we compare uncoupled fiber ribbons (UFR) to strongly coupled multicore fibers (SCMCF). UFRs are made of a set of single-mode fibers that can be managed independently: traffic routing may rely on the independent switching (InS) [4], and Propagation impairments can be modeled as in single-mode fibers. On the contrary, in SCMCF propagation, each core is strongly coupled to the others. This allows a reduction in the equivalent nonlinear efficiency which enables a mitigation of nonlinear propagation impairments (NLM) with an increase of the overall point-to-point capacity [5,6]. Such a capacity increase is obtained only if lightpaths are simultaneously added/dropped in/from all the fiber cores. So, each spatial superchannel on a given lightpath (LP) is forced to be allocated on the same route, implying joint switching (JoS) in reconfigurable add/drop multiplexers (ROADM) [4]. Transponders for SCMCFs are so based on multiple-input multiple-output (MIMO) coherent receivers with an overall dimension given by the dimension of the signal space - four in-phase (I) and quadrature (Q) on two orthogonal polarization states - multiplied by the number of cores [1]. This implies that using SCMCFs, if allocated traffic only partially fills the available spectral/spatial resources, residual capacity can be only exploited on the same route. So, traffic allocated on a given wavelength on all cores is forced to follow the same path, limiting the network flexibility. Considering only networking issues without including propagation effects, JoS forces networks to be less flexible, so, without specific operations on routing, it also yields a reduction in the overall network traffic load, at a given blocking probability [7]. Thus, JoS techniques have been analyzed focusing on algorithms for routing, space and spectrum allocation (RSSA) [4], and on complexity of switching architectures required to compensate for the performance gap with respect to independent switching, but without considering the NLM benefits. In [8,9], different switching node architectures are presented to overcome the JoS penalty. In [8], the core continuity constraint (CCC) [8] is proposed to enable high reduction in ROADM complexity. On the other hand, NLM in SCMCFs has been analyzed in point-to-point scenarios [5,6], showing that the intensity of nonlinear interference (NLI) scales down with the number of coupled cores, so enabling larger transmission capacity with respect to links relying on UFRs with the same SDM cardinality. In literature, the assessment is so far missing is a comparison of networking performances between the two SDM solutions - SCMCF and UFR -, including both the transmission advantages of SCMCFs and the switching benefits attainable when relying on UFRs. We approach such analysis by using the statistical network assessment process (SNAP) [10,11] on a network topology supposed to deploy SDM with cardinality of three, progressively loaded with traffic demands. As we aim at a networking comparison of the two physical-layer solutions, we keep as simple as possible the routing algorithm exploiting a simple k-th shortest path routing algorithm with first fit assignment both for spectral and spatial allocation. We consider different grooming sizes in demands to better fit requirements of the two solutions. We can evaluate networking benefits of NLM enabled by SCMCFs by studying the case of exploiting SCMCF without NLM. Results show how NLM in SCMCFs can significantly mitigate penalties due to JoS, but it is not able to completely compensate for it.

2. ANALYSIS

We assess performances of the two SDM solutions with cardinality of three deployed on the German network topology of Fig. 1. We study UFRs with both InS and CCC, and SCMCFs with JoS. So, we analyze the following SDM technologies: each bidirectional node-to-node amplified link is made by a pair of UFRs of three G.652 fibers (i) or by a pair of three-core SCMCFs (ii) with G.652 propagation parameters. Thus, attenuation is set to 0.2 dB/km, dispersion parameter to 16.7 ps/nm/km and nonlinearity coefficient to 1.3 1/W/km. We suppose amplifiers' spacing of 100 km and with noise figure (NF) of 5 dB for both SDM solutions. Nodes' excess loss of 18 dB is compensated by booster EDFAs with NF of 6.2 dB.

Transponders are supposed to generate spatial superchannels on the 50 GHz WDM grid on the C-band, so enabling transmission up to 96 lightpaths per fiber/core. Symbol rate is supposed of 32 Gbaud, including 28% protocol + coding overhead, setting spectral occupation of Nyquist-shaped channels to 32 GHz. The delivered bit-rate (Rb) is supposed to be bit-rate flexible and so adapted to the quality-of-transmission – the generalized signal to noise ratio (SNR) [10,11] – of the exploited lightpath. We do not focus on a specific hardware implementation and only suppose continuity in Rb vs. SNR with a request for a pre-FEC bit error rate (BER) of $4 \cdot 10^{-3}$.

Power levels are set according to the locally-optimized-globally-optimized (LOGO) control plane [12]. The generalized SNR of each LP including both amplified spontaneous emission (ASE) noise and NLI disturbance accumulation is evaluated using the incoherent Gaussian noise (iGN) model under the worst-case assumption of full spectral load [10]. The NLM is computed according to theoretical assessments of [6], where the optimum generalized SNR is displayed following the proportionality law:

$$\mathrm{SNR}_{\mathrm{opt}} \propto \left[\frac{4N_{\mathrm{CC}}}{(2N_{\mathrm{CC}}+1)\left(\sqrt{2N_{\mathrm{CC}}}\ {}^{8}/_{9}\, N_{\mathrm{CC}}^{-1}\right)}\right]^{2/3} \qquad (1)$$

Where N_{CC} is the number of coupled cores. Thus, for SCMCFs, the NLM enables the following SNR enhancement:

$$\Delta\mathrm{SNR} = \frac{\mathrm{SNR}_{\mathrm{opt}}^{\mathrm{SCMCF}}}{\mathrm{SNR}_{\mathrm{opt}}^{\mathrm{UFR}}} = \frac{3^{2/3}\, N_{\mathrm{CC}}^{\mathrm{SCMCF}}}{\left(2N_{\mathrm{CC}}^{\mathrm{SCMCF}}+1\right)^{2/3}} \qquad (2)$$

In the analyzed scenario, SCMCFs have $N_{CC} = 3$, so the ΔSNR respect to G.652 fiber is 2.3 dB.

The German topology of Fig. 1 is studied using SNAP with progressive traffic loading. As traffic model, we consider a uniform geographical distribution, thus the list of progressive node-to-node requests is randomly generated with uniform distribution: each node pair (s,d) has the same probability to be drawn for traffic allocation of grooming size R_G, if $s \neq d$. As SCMCFs need JoS, to avoid extra penalties due to inadequate granularity of a single request, we redo the study with different values of R_G for each request: R_G = 100, 150 and 200 Gbps for UFRs and 100, 150, 200, 400 and 600 Gbps for SCMCFs.

The routing and wavelength assignment (RWA) is performed computing routes through the k-th shortest path algorithm (k-max = 25). We use k-max = 25 to exploit the entire routing space, thus mitigating the wavelength contention caused by limited path diversity. Wavelengths are assigned on a first fit basis. Also, the spatial assignment - cores in SCMCFs and fibers in UFR – is performed on a first fit principle: if the request exceeds the core capacity on the spectral slot, the residual traffic is allocated on the second core and then on the third one. The computation of the shortest path is based on the QoT metric – the generalized SNR - as shown in [10]. We do not test advanced RSSA algorithms because we aim at assessing the impact of the physical layer on networking of different SDM solutions, independently of the routing algorithm. When using UFRs, JoS is not required, so we allocate traffic on LPs of each of the three available fibers, independently. Thus, R_G = 400 and 600 Gbps are not feasible for UFRs.

In traffic allocation, we exploit bit-rate overprovisioning. Thus, each time a channel or a spatial superchannel is allocated, Rb is set to the maximum value enabled by the route SNR and the residual rate ($\cdot$Rb- R_G) is used for future traffic requests on the same route. Note that, N_{CC} =1 for UFRs.

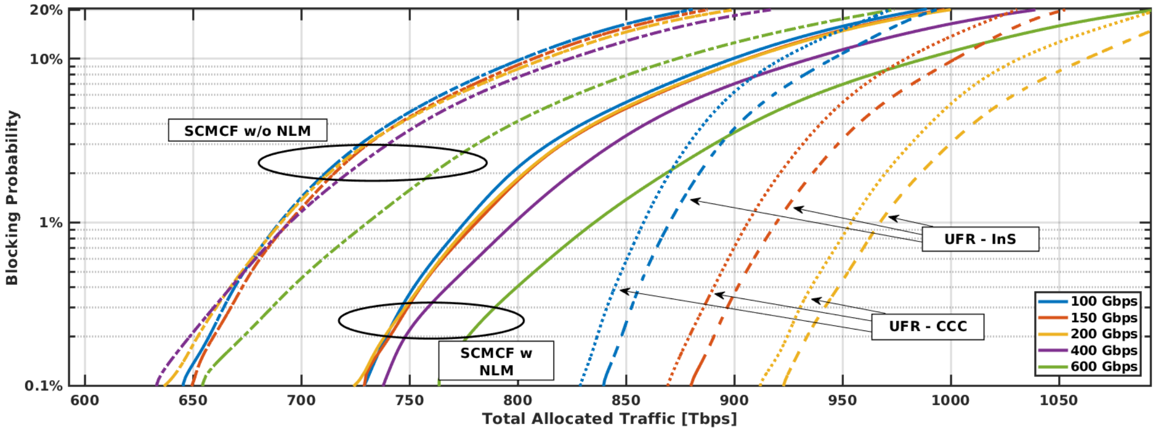

Fig. 2. Average Blocking Probability vs. total allocated traffic on the network for different traffic grooming as displayed in the legend.

Using SNAP with progressive traffic loading [11], we evaluate the following statistical metrics: blocking probability (P_B) vs. total allocated traffic. For each investigated scenario – SDM technology and grooming size – we generate NMC=25,000 Monte Carlo random traffic realizations up to the network saturation that we assume to be at P_B exceeding 20%. Then, averaged metrics are considered. The number of required Monte Carlo realizations N_{MC} has been chosen to guarantee metrics' stability. For each considered technology, we chose the value of R_G maximizing the total allocated traffic to compare performances at the optimum grooming size.

3. RESULTS

Fig. 2 presents SNAP results displaying the blocking probability P_B vs. the total allocated traffic averaged over 25,000 Monte Carlo runs. Each curve refers to a different grooming size, SDM solution and switching technique: SCMCF with NLM (solid line), UFR with CCC (dotted line) and UFR with InS (dashed line). The SCMCF without NLM case (dash-dotted lines) is also reported as a reference.

Curves related to UFRs at different R_G are almost parallel, both in case of InS and CCC, they present a rigid shift of about 50 Tbps each time R_G increases by 50 Gbps. UFR-CCC curves result to be a rigid shift to the left by 1.5% with respect to UFR-JoS. Thus, the penalty due to CCC seems to be limited.

For UFRs, better performances are reached for R_G=200 Gbps because, for this topology and physical layer, 200 Gbps is the grooming size better fitting the QoT distribution of the paths.

For SCMCF with and without NLM, we can observe a quite sensitive improvement for R_G=600 Gbps, that corresponds to three times the optimum grooming size of UFR. This because the capacity of a spatial superchannel along a path is slightly larger – because of NLM – than three times the UFR's on the same route.

In Fig. 3, traffic load results are shown as histograms at P_B = 1% and Tab. I lists their optimal values. Enlarging R_G from 100 to 150 Gbps, the growth of R_G by 50 Gbps increases the total allocated traffic of roughly 5 Tbps for SCMCF without NLM, and of 3 Tbps for SCMCFs with NLM. From R_G = 400 Gbps to 600 Gbps, an increase of R_G by 200 Gbps enlarges the total allocated traffic of 52 Tbps (7.5%) without NLM and of 45 Tbps (5.6%) with NLM (SCMCF).

Comparing SCMCF results with and without NLM of Fig. 3, benefits of NLM can be evaluated. As displayed in Tab. I, at the optimal R_G, NLM enables an increase of traffic from 731 Tbps to 837 Tbps (14.5%), but does not allow to reach optimal performances of UFRs which enable 954 Tbps in case of CCC and 969 Tbps with InS. So,

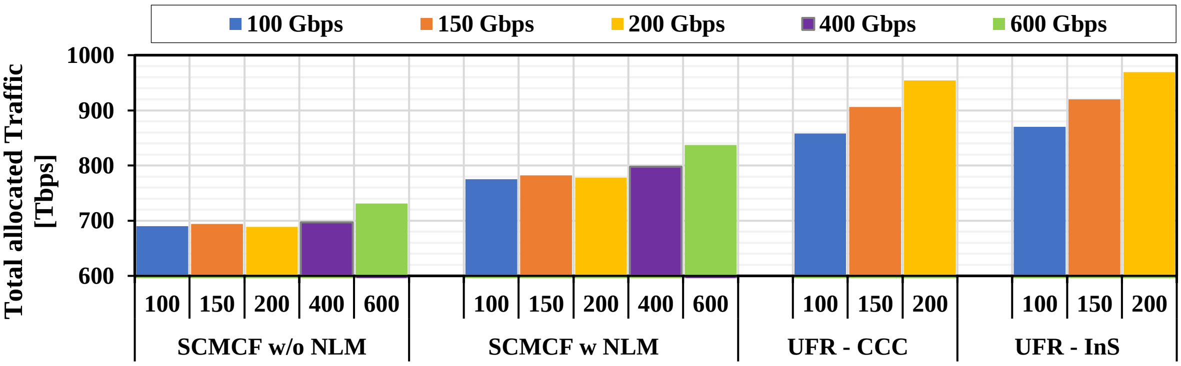

Fig. 3. Histograms of total allocated traffic for different grooming sizes at $P_B = 10^{-2}$.

at P_B = 1%, in the analyzed scenario, UFR is the most convenient SDM technique, enabling 14% more traffic with respect to SCMCFs with NLM, in case of CCC, and 15.8% in case of InS. Approaching P_B = 20%, i.e., network saturation, it can be observed that performances of SCMCFs are closer to UFR ones, but at P_B = 10%, SCMCF still underperforms UFRs of 4/7% (CCC/InS) in enabled total traffic: 988 Tbps vs 1030/1064 Tbps (CCC/InS) of UFRs. From a ROADM architecture complexity point of view, the InS requires an higher number of connections per degree, in fact, it increases quadratically with the number of fibers per ribbon. On the contrary, both CMCF and UFR-CCC require a ROADM complexity linear increasing with the number of cores/fiber per ribbon. Therefore, with 1.5% less capacity, UFR-CCC represents a good tradeoff between ROADM complexity and network flexibility.

Table 1. Summary of optimal results for the three analyzed scenarios @ $P_B = 10^{-2}$.

	SCMCF w/o NLM	SCMCF w NLM	UFR-CCC	UFR-InS
R_G [Gbps]	600	600	200	200
Avg. Total Traffic [Tbps]	731	837	954	969
Traffic Gain from SCMCF w/o NLM	0%	14.5%	31.5%	32.5%

4. COMMENTS AND CONCLUSIONS

We compared two SDM solutions with cardinality of three on a German network topology (Fig. 1). UFRs and SCMCFs solutions are assessed. We also considered different switching techniques – JoS and InS - and ROADM architectures CCC. We analyzed these technologies as deployed on the German network. As analysis tool, we exploit SNAP with progressive traffic loading to compute the blocking probability vs. the total allocated traffic. We considered bit-rate flexible transponders and explored different grooming sizes for uniform traffic requests. Optimal grooming sizes resulted to be 200 Gbps for UFRs and 600 Gbps for SCMCFs. Results displayed that, in the analyzed scenario the use of SCMCFs always underperforms UFRs in overall allocated traffic for reasonable values of P_B even if the gap reduces with the increase of P_B. At P_B = 1%, the underperforming gap is of about 15% while it goes down to 5% at P_Bs high as 10%. Regarding benefits of NLM, it strongly reduces rigidity introduced by JoS in SCMCF solution, enabling to increase the total allocated traffic from 731 to 837 Tbps (14.5%) at P_B = 1%, and from 935 to 1050 Tbps (12.3%) at very large P_B of 16%. From a practical point of view, it is useful to remark that the penalty of UFR-CCC with respect to UFR-InS is limited to 1.5% in the total allocated traffic, while the ROADM complexity is drastically reduced in case of UFR-CCC. So, the UFR-CCC seems to be a good compromise between ROADM complexity and total allocated traffic. Moreover, a general assessment on the presented analysis needs further studies considering different SDM solutions and topologies, larger SDM cardinality and specific RSSA algorithms since all these factors may show a different gap.

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