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A Statistical Analysis of Transparent Optical Networks comparing Merit of Fiber Types and Elastic Transceivers

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ABSTRACT

We perform a benchmarking of three different fiber types and two different implementation of flexible rate transceivers in a fixed-grid reconfigurable transparent optical network scenario. Results are obtained through a Monte Carlo based method called the Statistical Network Assessment Process (SNAP). Using the SNAP framework, we derive the statistics of the average bitrate per lightpath on a Pan European network scenario. We consider the average of such metric as a unique merit parameter to compare the use SMF, PSCF or NZDSF. We also consider two different implementations of elastic transceivers, namely one based on *pure* PM-M-QAM and the other using Time Division Hybrid Modulation Formats (TDHMF). TDHMF always outperforms PM-M-QAM, of 23% in SMF and PSCF and of 27% in the poorer transmission quality NZDSF. Results show that using flexible PM-M-QAM, PSCF are able to support a capacity increase in terms of average bitrate per LP of 48% with respect to NZDSF, while the improvement granted by SMF is 34%.

Keywords: impairment-aware networking, GN model, SNAP, flexible rate transceivers

1. INTRODUCTION

Over the last decade, the paradigm of transparent optical network has become a reality at every network layer, down to the transport – or WDM – level. The enabling technology step-forward has been the development of DSP-enabled transceivers based on multilevel modulation formats with coherent receivers and channel equalization [1]. In terms of transmission capacity, these technological advances have enabled, in the state-of the art commercially available systems, to operate at 100 Gbps/wavelength with spectral efficiency of 2 bit/s/Hz, on the 50 GHZ WDM grid. Moreover, in this transmission scenario, in-line chromatic dispersion compensation is not needed anymore [2], and the unique parameter for lightpaths' quality-of-transmission is the generalized optical signal to noise ratio (OSNR) including the accumulation of both the ASE noise introduced by the amplifiers and the non-linear interference (NLI) generated by the Kerr effect in fiber propagation [3]. From a network management point-of-view, these major advances have enabled to transparently route selected lightpaths in nodes, depending on the traffic request, and provided to maintain the overall lightpath QoT above the in-service threshold.

Within such an innovative framework, in back-bone transparent optical networks, the IP layer may operate logical links actually corresponding to physical lightpaths. The QoT parameter for lightpaths – the OSNR – is determined by the network topology as well as by the technologies characterizing the physical layer as, for instance fiber types and transmission techniques. Therefore, decisions about transmission equipments may induce major variations on how the network performs as a whole but, in general, we cannot translate transmission merits to networking benefits.

On the other hand, we are observing – and forecasting – an ever increasing traffic demand in IP networks [4], that carriers wish to satisfy maximizing the exploitation of installed transmission equipments and carefully addressing the upgrades, when needed. Hence, a careful assessment of network performances that can be enabled by the physical layer technologies of optical networks is required.

We have recently proposed a simulative framework that can be used for this purpose [5,6]. The Statistical Network Assessment Process (SNAP) is a Monte Carlo based analysis method that makes use of a detailed modelling for the physical layer of optical networks to derive a statistical characterization of several metrics of interests, such as capacity, quality of transmission and saturation. SNAP is able to characterize network metrics with respect to the set of possible allocation orders inside the network.

In this work, we use SNAP to compare different physical layer solutions on a pan-European network topology, considering the average bit-rate per lightpath as the metric to estimate the network performance. We suppose the network is operated on the C-band exploiting the 50 GHz grid, corresponding to a maximum of 96 channels per fiber. We focus our analysis on the merit evaluation for three different typical fiber types implementing the network uniform links: a typical SMF (α=0.2 dB/km, D=16.7 ps/nm/km, A_{eff}=80 μm^2), a large effective area NZDSF (α=0.22 dB/km, D=3.8 ps/nm/km, A_{eff}=70 μm^2), and a PCSF (α=0.167 dB/km, D=21 ps/nm/km, A_{eff}=135 μm^2). As transmission techniques, we suppose to exploit elastic transceivers working at the gross symbol rate R_{SG}=32 Gbaud corresponding to a net symbol rate R_s=25 Gbaud, supposing 28% FEC+protocol overhead. We consider two categories of transceivers: the ones that are able to switch among *pure* modulation formats (and in particular among PM-BPSK, PM-QPSK, PM-16QAM and PM-64QAM) and so enabling a coarse trade-off of rate vs. OSNR, and the ones that are able to *hybridize* pure modulation formats in time – time-division hybrid modulation formats, or TDHMF [8]– that enable a continuity in trading off the lightpath rate with its OSNR.

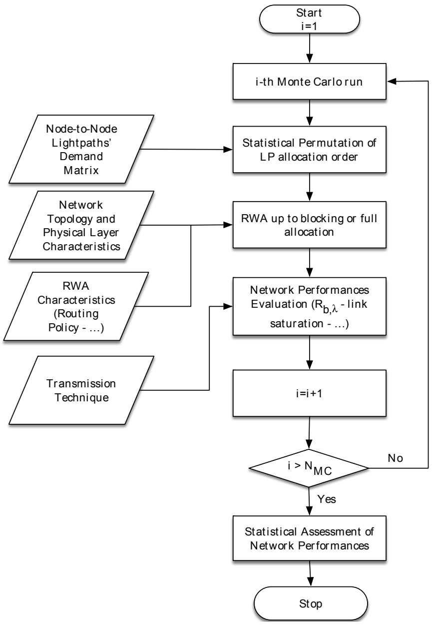

Fig1. Flowchart of the Statistical Network Assessment Process

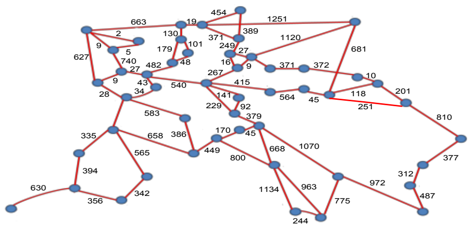

Fig 2. Pan-European Network Topology. Edge labels represents the link lengths in km.

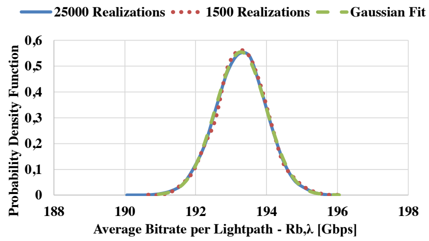

Fig 3. Probability Density Function of the Average BitRate per LP for different numbers of Monte Carlo runs.

2. THE STATISTICAL NETWORK ASSESSMENT PROCESS (SNAP)

The flow chart of Fig. 1 describes the proposed algorithm, while Fig. 2 represents the Pan-EU network topology it is applied to. SNAP makes use of the following input information:

1. A set of node-to-node lightpaths' demands organized in a matrix fashion: the connection matrix. Each element of the matrix $D_{i;j}$ represents the number of lightpaths to be allocated between node i and node j. While SNAP can work with any connection matrix, in this work we focus on one lightpath request for each node pair, i.e., on a *any-to-any* matrix. Since we aim at analyzing the potentialities of the physical layer of a fully re-configurable optical network, we consider demands expressed in terms of number of requested lightpaths' and not as data-rate. Practically, we do not consider traffic grooming in nodes.
2. A full description of the network topology and the characteristics of the physical layer, including fiber types, amplifiers and spectral use. The physical layer parameters are used to compute the generalized OSNR of each available lightpath. To this purpose, we use the incoherent GN-model (IGN) to accumulate the NLI introduced by fiber propagation, and we suppose full spectral load on each fiber link.
3. The characteristics of the Routing and Wavelength Assignment algorithm, such as the routing policy, namely the way in which fiber paths between nodes' pairs are computed and ranked. In this work, we use a shortest-link – highest QoT – LP allocation.
4. The transmission technique to determine the maximum allowable bit-rate of each LP given its OSNR and the related pre-FEC target BER, that we consider to be $BER_T=4\cdot 10^{-3}$.

Given this information, a Monte Carlo analysis is performed. During each Monte Carlo run the set of node-to-node ligthpaths' demands is randomly shuffled to vary the order in which requests are allocated. Given the randomly ordered list of connections, a RWA process starts. The RWA process tries to allocate each LP request according to the routing strategy. To do so, optically transparent paths able to accommodate the considered LP demands are searched across the network. In our analysis, we make use of a RWA based on the waveplane method [9,10] but, in general, any RWA can be used. The RWA process terminates when the complete set of demands has been considered. Depending on the traffic and network topology characteristics, the RWA process may successfully allocate all demands, or some network blocking may occur. After the completion of the allocation process, several network performance metrics can be computed for the i-th Monte Carlo run. In this work, we consider the average bit-rate per lightpath $R^{i}_{b,\lambda} = {}^{1}\!/_{N_{L,i}} \sum_{j=1}^{N_{L,i}} R_{b,j}$ Gbps, where $N_{L,i}$ is the number of allocated lightpaths during the i-th Monte Carlo run and $R_{b,j}$ is the bit-rate of the j-th LP. After the maximum number of Monte Carlo iterations N_{MC} has been reached, each metric can be statistically characterized with respect to the random allocation process of LPs. This means that the probability density function (PDF) of each analyzed metric can be derived, thus obtaining a statistical insight on network capabilities and critical aspects. The parameter N_{MC} is tuned observing the convergence of the PDF of the metric under investigations. In Fig. 3 we can observe that the distribution of the average bit-rate per lightpath converges to a Gaussian shape. The number of Monte Carlo iterations required for this to happen is greater or equal than 1500. To be conservative, in this work we use N_{MC} =2500.

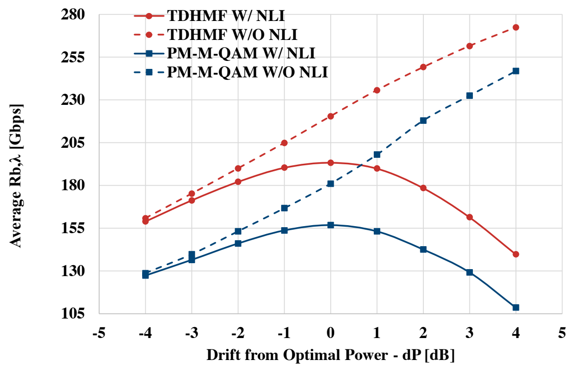

Fig 4. Pan-EU network made of uniform SMF fiber. Average bitrate per LP vs. detuning from the optimal power per channel envisioned by the LOGO approciach based on the IGN model.

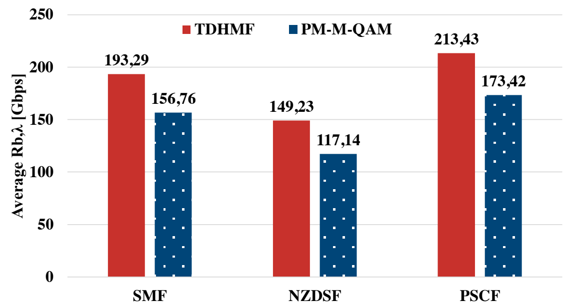

Fig 5. Bitrate per LP for each considered fiber type and the two considered transmission techniques.

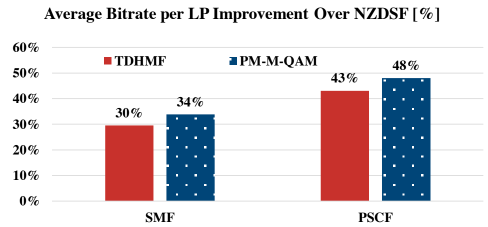

Fig 6. Average bitrate per LP improvement using SMF and PSCF with respect the NZDSF.

3. SYSTEM RESULTS

In this work, we present results obtained applying SNAP to the Pan-EU network topology described in Fig. 2. We suppose the network is operated according the local-optimized global-optimizes (LOGO) planning [10,11] that sets the power per channel on each fiber link at the level maximizing the generalized OSNR, according to the IGN-model. We suppose the worst case in terms of NLI generation defined by the full spectral load of each link. It is a conservative approach that does not cause large performance underestimate, as the NLI generation presents a weak dependence on the occupied bandwidth [12]. We use a detailed network description, including amplifier placement, that we suppose to be EDFAs with noise figure F=6 dB.

As a first analysis, we suppose the network is uniformly made of SMF links, and we apply SNAP considering the two elastic transponders: the ones based on pure formats –PM-M-QAM- and the ones based on hybrid formats –TDHMF. In order to demonstrate the importance of properly taking into account the NLI generation, we apply SNAP with and without the inclusion of such a disturbance. Moreover, with the purpose of showing the reduction of network potentialities induced by moving from the optimal LOGO planning, we apply SNAP also at power levels detuned from the optimal one. As previously stated, we consider the average bit-rate per LP $R_{b,\lambda}$as unique metric measuring the merit of different physical layer solutions. After the Monte Carlo analysis it results Gaussian distributed (see Fig. 3), and so to give a quick summary of the analysis, we take as merit parameter its average $<R_{b,\lambda}>$. Fig. 4 shows $<R_{b,\lambda}>$ vs. the drifting from the optimal power per channel envisioned by LOGO for the PM-M-QAM (blue lines) and TDHMF (red lines) transceivers both considering (solid lines) or excluding (dashed lines) NLI generation. Already at the first glance it appears unequivocal the need for the inclusion of the NLI generation in physical layer analysis. Otherwise, the optimal working point is not present, and the planning may lead to maximize the power per channel, according to the available EDFA maximum output power. Such an approach may induce a significant overestimation of network capabilities. For instance, for PM-M-QAM transceivers, drifting up 2 dB from the optimal LOGO power per channel, considering only ASE noise, on the dashed line we read $<R_{b,\lambda}>$=218 Gbps vs. the real $<R_{b,\lambda}>$=142.5 Gbps, roughly corresponding to 50% overestimate of network performance. A similar behaviour can be observed for TDHMF transceivers. So, we can state once again that the optimal network performances are granted by the LOGO planning and the analysis of the transmission level must include both ASE and NLI accumulation. Comparing the two categories of elastic transceivers, we observe that using TDHMF the network may ensure a maximum $<R_{b,\lambda}>$=193.3 Gbps vs. the maximum $< R_{b,\lambda} >$=156.8 Gbps for PM-M-QAM, hence granting more than 23% of average throughput enhancement.

After this first analysis, we consider only the correct physical layer modeling considering both ASE noise and NLI, and we suppose each link to be operated at its optimal power. Within such realistic hypotheses, we run SNAP considering the Pan-EU uniformly made of the other two typical fiber types: the large effective area NZDSF and a PSCF. Also in this case we test the two families of elastic transceivers: PM-M-QAM and TDHMF. From a point-to-point transmission point of view the hierarchy among the considered fiber is established [12]: the best fiber is the PSCF, followed by the SMF, while the one granting the worst transmission performance is the NZDSF. As shown in Fig. 5 this hierarchy holds also at the networking level. The advantage of TDHMF vs. PM-M-QAM is different fiber by fiber. We have already observed that it is 23% for SMF, while from Fig. 5 we evaluate it as about 27% for the NZDSF and about 23% for the PSCF. The reason for the better effect of TDHMF on NZDSF with respect the other fiber is caused by the large number of LP with poor QoT experiencing a greater benefit from the possibility to tune rate with continuity as granted by the TDHMF. Fig. 6 shows the quantitative evaluation of the hierarchy among fibers in terms of $<R_{b,\lambda}>$. In this figure, we take the NZDSF as a reference and plots the enhancement granted by the choice of the fiber and of the elastic transceivers. It can be observed that for the analyzed network topology and for PM-M-QAM, the SMF performs better than the NZDSF of about 34%, while the improvement of PSCF is 48%. In case of using TDHMF transceivers, benefits of SMF and PSCF is 4%-5% smaller because the NZDSF experiences a larger benefit from TDHMF.

4. CONCLUSIONS

In this work we review the Statistical Network Assessment Process to measure the impact of physical layer equipment on network performances. We choose as unique merit parameter the mean value of the average bit rate per lightpath and apply SNAP to a realistic Pan-European network scenario. We first show that a proper estimate of network potentialities needs the inclusion of both ASE noise and NLI impairments and the use of the LOGO strategy for planning. Otherwise, significant overestimation of network capabilities may be obtained. Then we compare the use of three typical fiber types: NZDSF, SMF and PSCF. We observe that the point-to-point transmission quality hierarchy is qualitatively kept also at the networking level, while the quantitative evaluation must be evaluated. We also compare different implementations of elastic transceivers, considering both pure PM-M-QAM and TDHMF. We observe that the poorer quality fiber – the NZDSF – experiences a larger advantage – roughly 27% - from the use of TDHMF with respect to the 23% evaluated for SMF and PSCF. Taking the NZDSF as a reference, we evaluate as 34% the throughput enhancement granted by the SMF and as 48% the one enabled by the PSCF, in case of using PM-M-QAM. Such advantages a roughly reduced of 5% in case of TDHMF, because the hybrid formats are more effective on the NZDSF.

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