Networking Benefit of Multi-Subcarrier Transceivers

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Abstract: We analyze the benefit of multi-subcarrier transceivers on two network topologies. We describe nonlinearities modeling challenges and demonstrate the existence of an optimal subcarrier symbol rate at network-level yielding average OSNR increase up to 0.7dB.
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1. Introduction

Multi-subcarrier (MSC) signals have been recently proposed as an alternative to standard single-carrier (SC) based systems. Thanks to modern high-speed Digital-to-Analog Converters (DACs) added to the flexibility of digital signal processing (DSP), electrically-generated MSC signals can be composed by a generic number of low symbol rate signals. The benefit of MSC over SC systems is their enhanced nonlinearity tolerance due to the Symbol Rate Optimization (SRO) phenomenon [1-3].

As the assessment of networking merits of transmission technologies through physical layer aware network modeling is a crucial need of operators and vendors, in this paper we evaluate the network benefits of SRO via MSC by comparing SRO-enabled gains in average Optical Signal-to-Noise Ratio (OSNR) over the routing space of a German and Pan-European topology, for different MSC configurations. We discuss modeling options for correct nonlinear interference (NLI) evaluation in transparent optical networks operated with MSC, comparing the Gaussian Noise (GN) [4] and the Enhanced GN (EGN) [5] models. We show the existence of an optimal symbol rate value for a given network topology, depending on its characteristics. At such value, we show OSNR gains (~0.7 dB) for both topologies.

2. NLI modeling in MSC networks

The GN model has been widely used for a fast evaluation of network performances: in particular its low complexity version based on the assumption of incoherent accumulation of NLI along multi-span links, the so-called Incoherent GN model (IGN), has been shown to deliver good accuracy when applied to high symbol-rate and long-distance transmission [6]. However, such approach does not hold for very short links and/or low symbol-rates, where it may incur into OSNR under-estimation error. In those cases, where MSC falls, the use of enhanced NLI estimation models, such as the EGN, is needed in order to achieve a reliable NLI estimation. In fact, EGN has allowed to clearly detail the NLI dependence on symbol-rate showing that SRO is an effective technique to mitigate non-linear effects [1-3]. Although the EGN increases substantially the complexity of NLI evaluation, it has recently been shown that for MSC systems at low symbol rate, where SRO is achieved, the NLI accumulation is almost linear over a very large set of conditions [7]. This result can be used to reduce complexity because NLI can be evaluated over a single span and then scaled up linearly without compromising accuracy.

In Fig. 1 we show the difference in estimated OSNR yielded by the EGN model ($OSNR_{EGN}$) and by the IGN model ($OSNR_{IGN}$), together with predicted SRO gain defined as the ratio between achievable OSNR by MSC and SC signals. We assume MSC transceivers operating at a total gross symbol rate of 32 GBaud, and number of subcarriers in the set {1,2,4,8,16}, corresponding to a subcarrier symbol rate R_S in the set {32,16,8,4,2} GBaud respectively.

We evaluate both models for the worst-case condition of full C-band spectrum occupation (81 channels operated on the 50 GHz grid), and assuming ideal phase noise mitigation at the receiver to remove the modulation format dependency of the EGN model [2]. Uniform, 100 km-spans of Single Mode Fiber (SMF) with 0.2 dB/km attenuation,

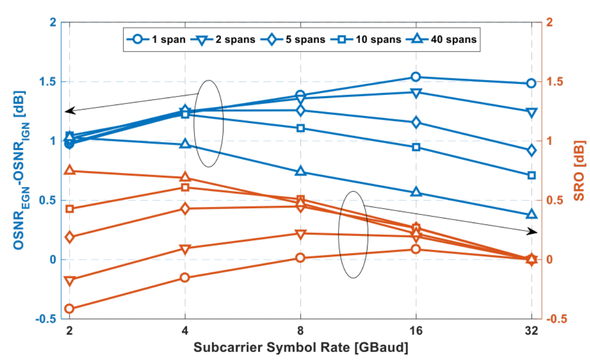


Fig. 1: Gap between OSNR estimated by the GN and EGN models (left axis) and SRO gains predicted by the EGN model relatively to the baseline 32 GBaud case (right axis).

16.7 ps/nm/km dispersion and 1.3 1/W/km non-linear coefficient are assumed. We assume each span to be operated at its optimal power, as predicted by either the IGN or EGN models. Span losses are recovered by 5 dB noise figure EDFAs.

A first key observation from Fig. 1 is that even for transmission at 32 GBaud (SC), the GN model significantly under-estimates OSNR for short links (peaking at ~1.5 dB for single-span), while this gap progressively reduces as the link length is increased, reaching about ~0.5 dB after 40 spans. Also, note from Fig. 1 that the optimum number of MSC subcarriers is distance dependent. For typical average link lengths of 10-40 spans, the optimum number of subcarriers is found in the range of 8-16 (R_S = 2-4 GBaud), corresponding to SRO gains of approximately 0.8 dB. Note also that, for very short links, MSC signals can yield up to 0.5 dB OSNR penalties.

In the following, we will focus on studying how much of this SRO gain can still be preserved in transparent meshed network scenarios where route lengths are highly heterogeneous.

3. Network Scenarios and Analyses

We consider the two network topologies of Fig. 2: a smaller German network topology (Fig. 2a), and a larger Pan-European one (Fig. 2c). Topologies data are summarized in the caption of Fig. 2. Node-to-node fiber links are assumed to be bidirectional, uniform and uncompensated fiber-pairs consisting of 100 km SMF-spans. The same fiber parameters and MSC configurations of Fig. 1 are used in the following derivations.

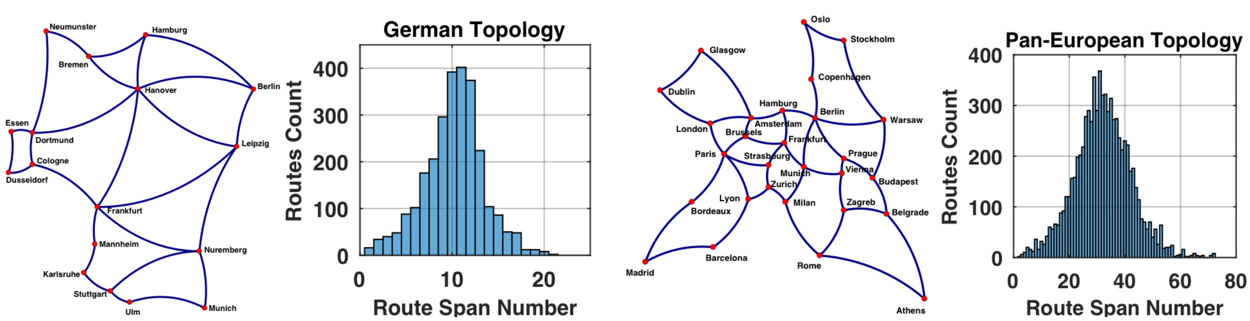
We compute the routing space of both networks, i.e. the set of k-simple-shortest paths between any pair of nodes. We assume a hop-count based routing policy, setting k=10 to have a sufficiently wide set of possible routes. The total number of routes in the set is equal to 2720 and 7560 for the German and Pan-European network, respectively. The distributions of routes lengths in terms of number of spans are reported in Fig.2b and Fig.2d. Average route lengths are 10.2 and 32.0 spans, i.e. 1020 and 3204 km for the German and Pan-European case, respectively.

For each route in the set, we compute its OSNR using either the IGN model, or the EGN model for each subcarrier configuration. Then, for each case, we evaluate the OSNR distribution of the routes and compute the average OSNR value of the routing space for each MSC scenario. No traffic allocation, i.e. routing and wavelength assignment (RWA), is considered in this paper. Nevertheless, this type of studies, like the ones presented in [6], for MSC systems could strongly benefit from the quasi-linear NLI accumulation behavior found in [7], which allows to speed up the computation even if it requires to apply the more complex EGN.

Fig. 3a depicts the OSNR distribution computed through the EGN model for the two extrema of the MSC configurations: 1×32 GBaud SC and 16×2 GBaud MSC. The MSC solutions enable SRO for the routes in the 12 to 20 dB OSNR range, which inversely corresponds to length range from 500 to 3000 km. In this interval, the OSNR distribution of the routes appears to be right-shifted towards higher OSNR values. In the OSNR range from 20 to 25 dB (from 500 to 300 km in length), no significant distribution variations are evident. Finally, in the high OSNR range, the considered 16×2 GBaud solution is harmful, and the OSNR of shortest routes (<300 km) gets degraded, as highlighted in Fig. 1.

Fig. 3b represents the average OSNR across the routing space of the German topology for all the considered MSC configurations computed through the IGN model (black dashed curve) and the EGN model (blue solid curve). The IGN curve shows no R_S dependency as such model is not able to highlight SRO. Depending on line terminal transceiver flexibility, such error can have a minor impact on capacity evaluation [6].

Focusing on the MSC results, it is evident how decreasing R_S allows to increase the mean OSNR of 0.55 dB from 17.45 dB at 1×32 GBaud, up to 18 dB at 8×4 GBaud MSC setup. For even higher subcarrier number, the average OSNR decreases, since the number of short routes that gets degraded by MSC increases.



a) b) c) d)

Fig. 2: Analyzed topologies. **a)** German network, 17 nodes, 26 links, average node degree 3.06, average link length 207 km, **b)** Lightpath span number distribution in the German network routing space, **c)** Pan-European network topology, 28 nodes, 41 links, average node degree 2.93, average link length 637 km. **d)** Lightpath span number distribution in the Pan-EU network routing space.

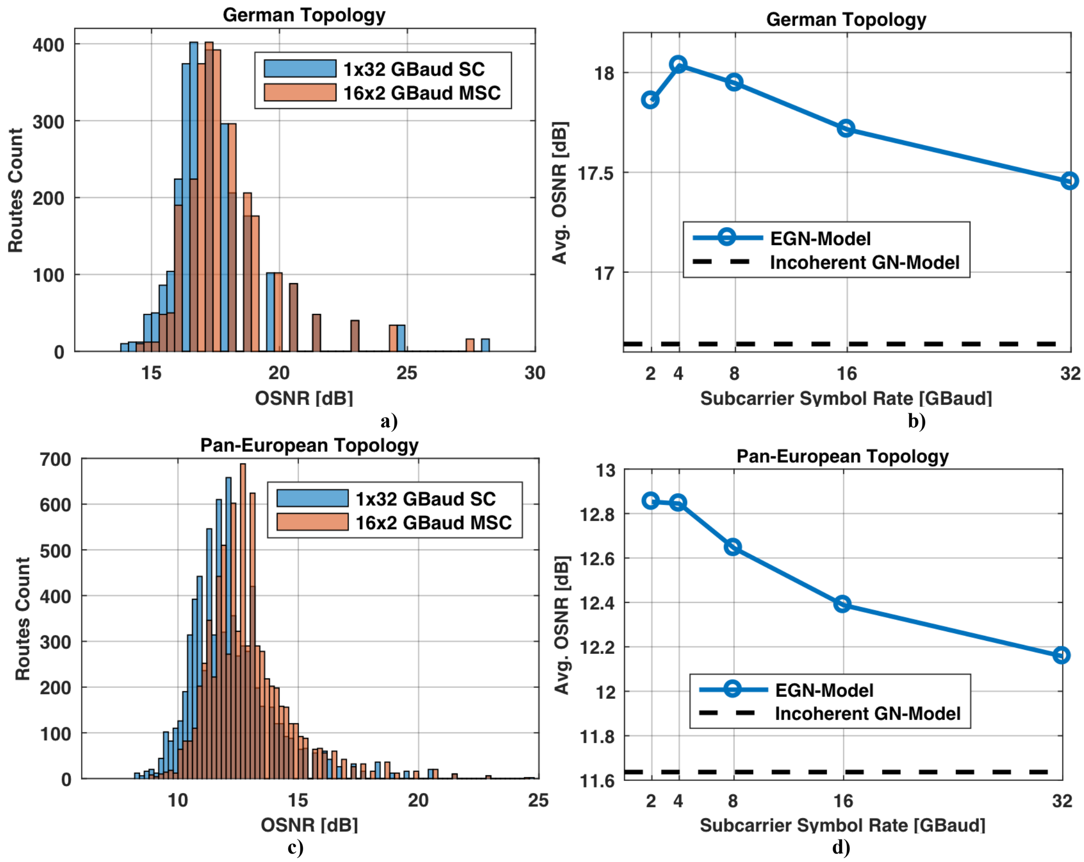


Fig. 3: OSNR distribution of the routes for two MSC configurations (1×32 GBaud, 16×2 GBaud) for the **(a)** German and **(c)** Pan-European topologies. Average route OSNR comparison vs SC symbol rate for the **(b)** German and **(d)** Pan-European topologies. IGN model is included

Results for the Pan-European topology are shown in Fig. 3c and Fig. 3d. Fig. 3c depicts the EGN-computed OSNR distribution both for the 1×32 GBaud SC and for the 16×2 GBaud MSC configurations. Due to the average longer route lengths of this topology, the benefit of SRO using 2 GBaud MSC is more evident. For this topology, the routes whose OSNR gets degraded with MSC are only 2. Thus, it is reasonable to expect a larger benefit due to MSC, since a wider set of routes undergoes SRO. This is confirmed in Fig. 6, where the average OSNR of the routes for each transceiver configuration is depicted. Once again, SRO is evident moving from 1×32 GBaud SC to the optimal 16×2 GBaud MSC. In such case, the SRO benefit at network level is 0.5 dB, moving from 12.15 dB average OSNR in the 1×32 GBaud configuration to 12.85 dB for 16×2 GBaud MSC. Finally, we consider the optimal symbol rate equation (Eq. 10 in ref. [3]) and compute the optimal R_S associated to the average route length of the routing spaces of the two topologies. For the German topology, having an average route length of 10.2 spans, the optimal network symbol rate is ~5 GBaud, for the Pan-European network, with 32.0 spans of average route length, the optimal R_S is ~3 GBaud. These values are in agreement with the previous results of Fig. 3b and Fig. 3d.

4. Conclusions

We showed how SRO achieved through MSC transceivers can improve average OSNR of routes in two network scenarios. In a national (German) topology with average link length of about 1000 km the gain is 0.55 dB while in a longer continental (European) topology the improvement can reach up to 0.7 dB at optimal R_S.

5. References

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