On the Accumulation of Non-Linear Interference in Multi-Subcarrier Systems

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Abstract *We study the accumulation of non-linear interference generated in uncompensated links by multi-subcarrier channels: at optimum symbol-rate we found an almost linear growth. This results allow a simplified non-linear modeling for this class of systems.*

Introduction

In the last years several studies and experiments have clearly reported on the existence of an optimum symbol-rate that minimizes the nonlinear interference (NLI) noise generated along signal propagation in dispersion uncompensated optical links[1–5]. Multi-subcarrier (MSC) systems have emerged as an effective solution for achieving symbol-rate optimization (SRO) while keeping the same complexity of a standard single carrier approach. In fact, theoretical models for NLI, such as the enhanced Gaussian noise (EGN) model[6], show that optimal symbol-rate for standard links always fall in the range between 2 to 4 Gbaud: a value too small for a single carrier solution requiring an unfeasible amount of transceivers.

Analysis of NLI accumulation based on GN-model in multi-span systems for single carrier channels predicts a super-linear growth along the link due to a coherent interaction between non-linearity generated in each span[7]. In this paper we consider the propagation of multi-subcarrier signals. We provide a comprehensive analytical and simulative study together with an experimental validation carried out with 31 channels modulated as MSC using the PM-16QAM format. We show that for symbol-rates that are optimal at long distance (<4 Gbaud) the accumulation is almost linear: this finding allows to simplify the NLI prediction in MSC systems and can be envisioned to allow future application in effective network planning.

Nonlinear interference estimation

Analyzing the NLI accumulation in several system conditions, it appears that P_{NLI} dependence on N_{spans} can be accurately described by the following expression[8]:

$$P_{\mathrm{NLI}} \approx P_{\mathrm{NLI}}^{(1)} \cdot N_{\mathrm{spans}}^{1+\varepsilon}, \quad (1)$$

with $\varepsilon > 0$, where $P_{\mathrm{NLI}}^{(1)}$ is the NLI evaluated after the first span. This effect has been verified experimentally[8,9] for single carrier systems. In this paper we consider MSC systems analyzing the accumulation of NLI and we evaluate the parameter ε for different subcarrier symbol rates.

We first conduct an analytical NLI estimation based on the EGN model, since the simpler GN-model is not adequate in this scenario where we employ multi-subcarrier channels. GN-model is symbol rate agnostic and in fact it was not able to capture the SRO demonstrated using the EGN. The EGN requires the knowledge of the modulation format transmitted on each channel because the amount of NLI depends on it: higher cardinality formats generate a stronger NLI. This increase of NLI is mainly due to nonlinear phase noise (NLPN) that has been shown to have a very long time-correlation[10], so it can be easily removed by optimized carrier and phase estimation (CPE) algorithms. When completely removing NLPN from NLI it was found that the signal performance can be accurately evaluated by the EGN considering a single-amplitude format, such as PM-QPSK[5]. For this reason, EGN results shown in this paper are all based on this assumption. Throughout all the paper P_{NLI} is defined as the total amount of NLI impacting a whole channel so that it is independent of subcarrier symbol-rate.

The second and the most relevant NLI estimation we conduct is based on experimental measurements taken on a recirculating loop. In this case we derive P_{NLI} from BER obtained at the output of the specific DSP applied to recover the MSC signal. The procedure adopted is the following: first from BER we get $\mathrm{SNR}_{\mathrm{meas}}$ through the relationship peculiar for the modulation format:

$$\mathrm{SNR}_{\mathrm{meas}} = \Psi^{-1}\left[\mathrm{BER}\right]. \quad (2)$$

Under the typical assumption that NLI is a Gaussian additive noise with respect to ASE noise and considering also a further equivalent noise contribution (P_{B2B}) to take into account the

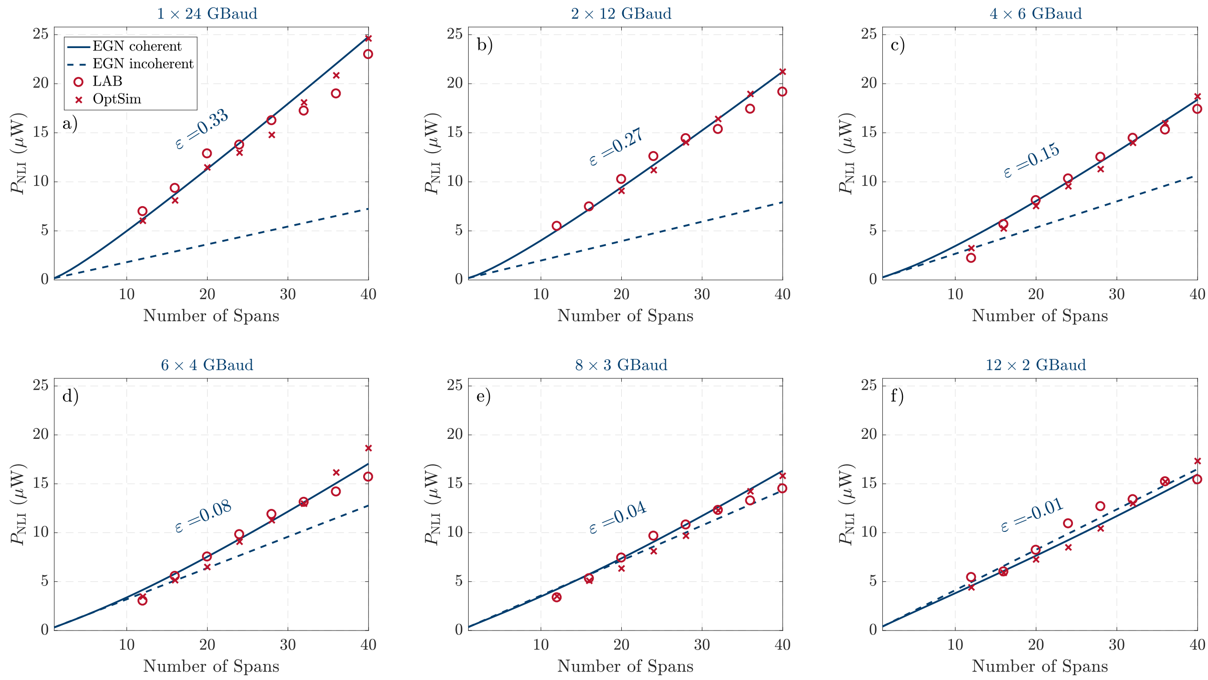

Fig. 1: Dependence of the generated NLI power on propagation distance (number of fiber spans) and number of electronic subcarriers at a transmitted power of 0 dBm per optical channel. a) 1×24 GBaud, b) 2×12 GBaud, c) 4×6 GBaud, d) 6×4 GBaud, e) 8×3 GBaud and f) 12×2 GBaud.

back-to-back penalty, we have that

$$\mathrm{SNR}_{\mathrm{meas}} = \frac{P_{\mathrm{tx}}}{P_{\mathrm{ASE}} + P_{\mathrm{B2B}} + P_{\mathrm{NLI}}} \tag{3}$$

where P_{ASE} is the total amount of ASE noise accumulated that can be analytically evaluated as $P_{\mathrm{ASE}} = hf_0 F G R_s^{\mathrm{MSC}} N_{\mathrm{spans}}$. h is the Planck constant, f_0 is the channel frequency, F is the EDFA noise figure and R_s^{MSC} is the aggregate symbol rate for each channel that we use as a reference bandwidth for SNR definition. After P_{B2B} is derived from back-to-back measurement based on the SNR penalty, we can easily derive P_{NLI}.

Finally a third NLI estimation has been obtained using numerical simulation carried out with the OptSim simulator. After accurate parameter identification, with full band split-step simulations we obtain BER. Then, using the same procedure described above for the experimental NLI estimation we were able to get P_{NLI}.

Experimental setup and results

The experimental setup is the same considered in[5]: here we report only main parameters, for more details refer to the cited paper. We transmitted 31 channels at an aggregate symbol-rate of $R_s^{\mathrm{MSC}} = 24$ GBaud per optical channel with an inter-channel separation of 28 GHz. Applying digital subcarrier multiplexing, each channel is then generated either as 1×24 GBaud, 2×12 GBaud, 4×6 GBaud, 6×4 GBaud, 8×3 GBaud or 12×2 GBaud. The recirculating loop is composed of 4 spans of pure silica core fiber (PSCF) with average length of 108 km, dispersion parameter of 20.12 ps/(nm · km) and attenuation coefficient of 0.162 dB/km. EDFA noise figure was evaluated to be $F = 5$ dB, and EDFA gain $G = 18.2$ dB, equal to the span loss due to the PSCF fiber and splices to SMF adding some extra loss. At the receiver, only the central channel is coherently detected and sampled by a 50 GSa/s real-time oscilloscope. Then, digital signal processing of the received MSC signal starts with front-end correction, chromatic dispersion compensation, frequency offset and carrier phase estimation (CPE). To satisfy the condition that all NLPN is compensated by CPE, we implemented a fully data-aided receiver with memory optimization as presented in[5]. Finally, the signal is decoded and the average BER among all subcarriers is counted.

In Fig.1 we report the three NLI estimations: blue solid line for the EGN coherent model, red circles for the experiment (LAB) and red x-marks for the simulation (OptSim). Each subplot refers to a different symbol-rate for the subcarriers. We also report a blue dashed line that has been obtained assuming an incoherent accumulation of NLI, in which case it is only evaluated at the end of first span and then added up linearly for the rest of the link ($\varepsilon = 0$).

We have considered a transmitted power per channel of 0 dBm, that is very close to the optimal

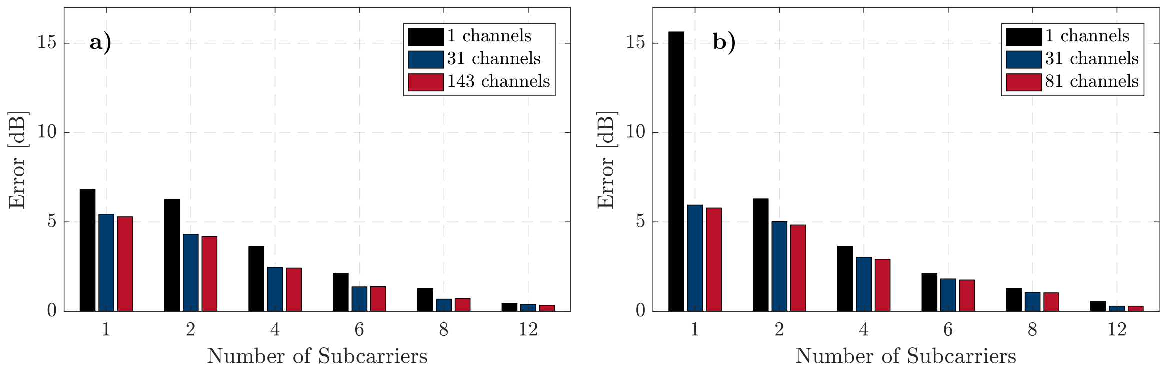

Fig. 2: Maximum absolute error in P_{NLI} estimation using the EGN incoherent accumulation as a function of symbol-rate. For each number of subcarriers, each bar refers to a different number of channel: 1, 31 and full C-band. a) 28 GHz of inter-channel spacing; b) 50 GHz of inter-channel spacing.

power for all distances in the measured range up to 40 spans. Experimental and simulation data are available only after 3 recirculations because BER for short distances is too low and not reliable.

First of all we can see a very good agreement between all three NLI estimations for all considered multi carrier symbol-rates. Moreover, SRO is also clearly visible: P_{NLI} at the end of the link is decreasing when reducing the symbol-rate. In Fig. 1 we observed an important new property of NLI accumulation: reducing the symbol-rate it tends to become more and more incoherent coming close to the linear behavior. This effect can be quantified determining the ε parameter for each case: we report the numerical value in each subplot. Starting as high as $\varepsilon = 0.33$ for the single carrier, it is reduced to $\varepsilon = 0.04$ for 3 Gbaud and we even found it to be slightly negative ($\varepsilon = -0.01$) for 2 Gbaud.

Simulation results

To further prove the validity of the incoherent accumulation of NLI for low symbol-rates, considering as a starting point the same setup as in the experiment presented in the previous section, we extend the results using the EGN model. Results are presented in Fig. 2 as the maximum absolute error in the P_{NLI} estimation over all spans when using the incoherent accumulation compared to the standard EGN model. We extend the analysis up to 50 spans and we also analyze a different channel spacing (50 GHz). The dependence of the error as a function of the total number of channels propagating in a fiber is reported for all number of subcarriers corresponding to the symbol-rate analyzed. The incoherent accumulation is always a good approximation for the 2 Gbaud case: down to the single channel case the maximum absolute error is always below 0.45 dB and 0.56 dB, respectively for the 28 and 50 GHz channel spacing. Moreover, differences in P_{NLI} are mitigated by a factor of 1/3 when used to evaluate OSNR margin[11], further reducing the performance estimation error. Throughout all analyzed cases this error is limited to less than 0.2 dB.

Conclusions

We analyzed the NLI accumulation in multi-subcarrier systems observing that for symbol-rates as low as 2 Gbaud the growth is almost linear. Experimental validation confirms analytical model and simulation results. In the analyzed scenario based on PSCF fiber, the incoherent accumulation assumption always deliver a performance estimation error below 0.2 dB. This approach strongly simplifies the design of optical links based on MSC channels that take advantage of SRO. Physical layer aware network planning tools can also benefit from this approach because it speeds up the NLI evaluation.

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