On the Nonlinearity Tolerance of Using Short DM Blocklengths for SOA Booster in Coherent Systems

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Abstract: SOA nonlinearity tolerance is experimentally demonstrated for 68 Gbaud single-carrier/8-carrier PCS-64QAM systems. 1.4 dB additional output power is obtained with a 256 blocklength ESS, at the similar optimal SNR and rate loss of long blocklength CCDM.

1. Introduction

With the advent of 400G transceivers and the upcoming 800G generation, the coherent technology plays a key role for metro/core networks and possibly access networks. System vendors have extensively investigated probabilistic constellation shaping (PCS) techniques, which enable to approach Shannon-capacity [1]. PCS constellations are typically generated by a distribution matcher (DM) together with the probabilistic amplitude shaping (PAS) scheme [1]. Furthermore, the short DM blocklength has been demonstrated with constant composition distribution matching (CCDM) and enumerative sphere shaping (ESS) [2,3] to provides a better nonlinear (NL) tolerance in optical transmission systems, at a cost of increasing rate loss.

Commercial high-bandwidth coherent driver modulator (HB-CDM) targets a nominal symbol rate beyond 100 Gbaud, which degrades the optical output power and hence requires an amplifier to guarantee the expected output power. Semiconductor optical amplifier (SOA) serving as a booster is of interest due to its small size, low power consumption and high design flexibility [4]. However, the SOA nonlinearity becomes a barrier for the overall performance of coherent systems. In the last few years, several compensation techniques have been proposed to mitigate SOA NL phase distortion both in optical and digital domains. For instances, the digital SOA NL compensation based on fourth-order Runge-Kutta method has been experimentally demonstrated in E-band [5]. On the other hand, NL compensation technique based on optical phase conjugation in C-band is proposed in [6]. Recently, the NL compensation based on holding beam technique has been demonstrated [4]. However, these techniques require additional hardware [4, 6] or could lead to higher power consumption of the DSP [5] making it necessary to explore other solutions.

In this paper, we explore for the first time the performance gain of using short DM blocklengths to enhance the SOA NL tolerance. The benefit of short DM blocklength against SOA nonlinearity is experimentally demonstrated with 68 Gbaud single-carrier and 8-carrier PCS-64QAM signals in L-band, showing up to 1.4 dB further boosted output powers when applying 256 blocklength ESS compared to long blocklength CCDM, while retaining a similar rate loss. Compared to other NL compensation methods in literature, our proposal exploits the natural application of PCS employing a finite DM blocklengths, with almost no additional complexity. Additionally, we study how the gain provided by short blocklength can be combined with carrier phase recovery (CPR) optimization.

2. Experimental Results and Discussion

The experimental setup is shown in Fig. 1(a). One tunable laser source (TLS) at 1576 nm wavelength is used at the transmitter side. The single-carrier/ 8-carrier dual-polarization 68 Gbaud PCS-64QAM signals of entropy

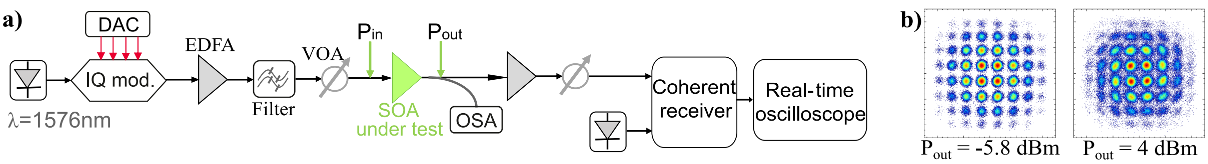

Fig. 1: (a) Experimental setup; (b) Example of 1-carrier PCS-64QAM CCDM128 constellations in linear ($P_{out} = -5.8$ dBm) and nonlinear ($P_{out} = 4$ dBm) regions.

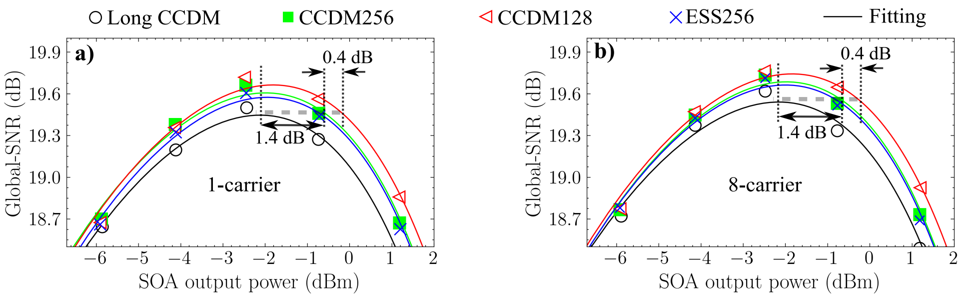

Fig. 2: Global-SNR versus SOA output powers for (a) 1-carrier and (b) 8-carrier using pilot-only CPR.

4.5 (corresponding to ~400G net capacity, assuming 28% FEC overhead and 8% pilot/protocol overheads) are generated by a 120 GSa/s digital-to-analog converter (DAC) and modulated onto the optical carrier by an IQ modulator. Note that the QPSK pilots are inserted every 48 symbols to help the DSPs. We put an L-band Erbium-doped fibre amplifier (EDFA) at the output of the IQ modulator in order to be able to vary the SOA input powers in a wide range. An optical bandpass filter is applied to remove the out-of-band amplified spontaneous emission (ASE) noise. We tune the input powers to the SOA under test by means of a variable optical attenuator (VOA). In order to operate at realistic conditions, the working temperature of SOA is kept to be 45°C and the current is 150 mA, which gives a small signal gain of ~14 dB. At the receiver side, the signal is amplified by another L-band EDFA to adjust and keep constant the input power to the coherent receiver, where the signal is mixed with a TLS LO and converted into the electrical domain using four balanced photodetectors. The electrical signals are sampled with an oscilloscope operating at 256 Gsample/s. The digital signals are then processed offline, including the front-end compensation, resampling, equalization and CPR. Fig. 1(b) presents the PCS-64QAM constellations at the output powers of −5.8 dBm and 4 dBm with pilot-only CPR. It is clearly seen that the NL phase rotation appears at the high power. We discuss further the CPR impact in subsection 2.2. Global signal-to-noise ratio (Global-SNR) is used as a metric for the achievable capacity of the system with any number of carriers (including single carrier) [2]. For an M-carrier system, it is computed as: Global-SNR $= \prod_{m=1}^{M}[1+SNR_m]^{1/M}-1$, where SNR_m is the SNR of the m-th subcarrier.

Table 1: Rate loss (bit/1-D symbol) of CCDM and ESS with different blocklengths.

Blocklength	128	256	1024	1536
CCDM	0.073	0.046	0.013	0.010
ESS	0.028	0.014	-	-

2.1. *Gain of Short-DM Block Length for Single-Carrier and DSCM Signals*

It has been shown that the SNR performance of short DM blocklengths of CCDM and ESS are similar in the presence of the fiber nonlinerity [2]. It is worth noting that short blocklength ESS (i.e., 256) shows a rate loss approximately equal to that of long blocklength CCDM (i.e., 1024 and close to the one of 1536), while remaining a good NL performance (see Tab. 1). In what follows, we assess in detail the SOA NL performance gain when using short CCDM blocklengths of 128 (CCDM128), 256 (CCDM256) and short ESS blocklength of 256 (ESS256), in comparison to long CCDM (of blocklength 1536). Figs. 2(a) and (b) present the Global-SNR as a function of SOA output power for 1-carrier and 8-carrier, respectively. Note that, a simple pilot-only CPR is applied here. Taking the optimal SNR performance of long CCDM as a benchmark, a 1.4 dB additional output power can be achieved when reducing the blocklength to 256. The rate loss of ESS256 is close to that of long CCDM, while the rate loss of CCDM256 reduces ~0.03 bit/1-D symbol compared to that of long CCDM. An 0.4 dB extra output power is obtained if we further decrease the blocklength to 128, however, at the cost of increasing the rate loss of both CCDM128 and ESS128 (not shown here for the sake of simplicity). The similar improved output powers are observed for both single and 8-carrier signals, confirming the effectiveness of using short DM blocklengths against SOA nonlinearity. This gain comes from the fact that the power variation within the carrier lifetime of SOA reduces, thanks to the constant composition property of DM. Hereafter, we consider only the results of long CCDM and ESS256, due to its similar rate loss, for the sake of clarity.

2.2. *Impact of CPR on SOA NL Performance*

In order to highlight the role of CPR on NL phase noise compensation, we enhance the current CPR performance by cascading the simple pilot-only CPR (called CPR1) to a blind feed-forward CPR based on direct-decision maximum likelihood (DD-ML), at the cost of extra complexity. Hereafter, we refer the CPR1 followed by DD-ML stage as CPR2. For a fair comparison, we first find the optimal CPR2 number of taps. The number of taps for pilot-aided CPR stage are set to be 35. We study the Q^2-factor of 1-carrier ESS256 signals when varying the filter taps number of DD-ML stage of CPR2 at the output power of 4 dBm (Fig. 3). We can see that the optimum

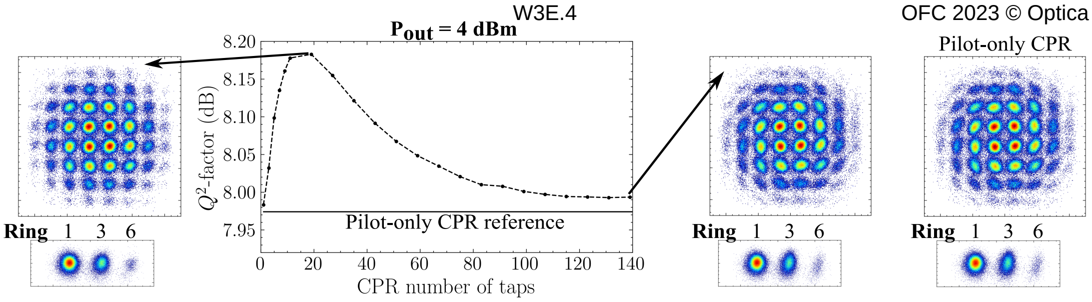

Fig. 3: Q^2-factor versus CPR blocklength when cascading pilot-only CPR to DD-ML stage. Examples of ESS256 constellations with pilot-only and enhanced CPR, along with folded constellation points of 3 amplitude levels.

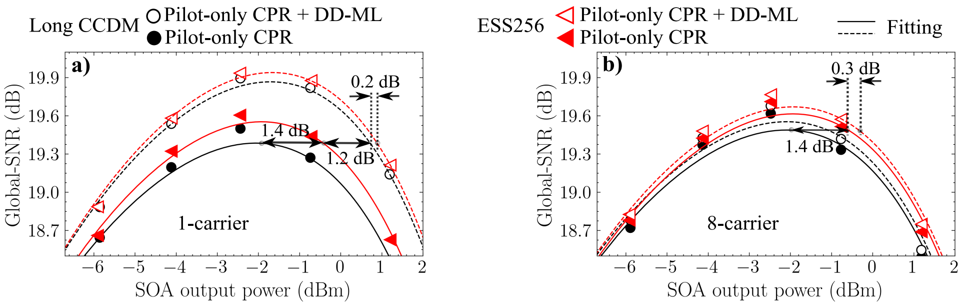

Fig. 4: Global-SNR versus SOA output powers using pilot-only and enhanced CPRs (cascading with DD-ML) for (a) 1-carrier and (b) 8-carrier.

number of taps is about 15 where a Q^2-factor improvement of $\sim$0.2 dB can be observed. For lower number taps, CPR2 is affected by wrong decisions, whereas for larger number of taps the fast tracking required by SOA nonlinearites is not achieved. Insets are examples of constellations at the optimal Q^2-factor and at 141 taps of CPR2, in comparison to the one of CPR1. In order to better visualize the effect of nonlinearity, the *demodulated* constellation points corresponding to the same symbol amplitude are folded and it is illustrated with 3 rings (out of 8 rings of PCS-64QAM) in Fig. 3. Taking ring 3 as a reference (good trade-off between linear (inner rings) and nonlinear (outer rings) effects), the variance ratio (defined as ratio between radial (amplitude) and orthoradial (phase) variances) of CPR1 is 2.03. It reduces to 1.38 by using CPR2, owing to the enhanced DD-ML stage.

In light of optimal CPR number of taps, we assess the performance using CPR1 and CPR2 in Fig. 4(a) and (b) for 1-carrier and 8-carrier, respectively. Note that other DSP parameters are not modified compared to the previous results. Taking the optimal SNR of CPR1 based long CCDM as the benchmark, besides 1.4 dB extra power by using ESS256, we observe up to 1.2 dB further boosted SOA output powers thanks to CPR2 for 1-carrier long CCDM. Only $\sim$0.2 dB more power can be boosted when using 1-carrier ESS256 with CPR2. The gains of CPR2 for 8-carrier are marginal, only $\sim$0.3 dB output power are boosted when using ESS256. It is due to the fact that phase noise caused by the SOA cannot be tracked by CPR2 in this case. Even the gain is not that high, it still encourages to find a proper CPR design to boost SOA output power, however, the complexity should be carefully considered.

3. Conclusion

We have experimentally investigated the NL gain for SOA booster by using short DM blocklengths in 68 Gbaud 1-/ 8-carrier PCS-64QAM systems, showing the similar performance between two kinds of signals. At 256 DM blocklength, up to 1.4 dB additional output power can be boosted using ESS256, at the similar optimal SNR performance and rate loss of long DM blocklengths. The use of short DM blocklength provides the SOA NL gain without the need of applying complex NL compensations.

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