Achievable Mitigation of Nonlinear Phase Noise through Optimized Blind Carrier Phase Recovery

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ABSTRACT
Partial mitigation of nonlinear phase noise by standard carrier phase recovery has been reported both, experimentally and through simulations. In this paper we quantify the achievable mitigation by using different implementations of the carrier phase recovery. All the approaches are based on the widespread blind phase search algorithm but follow different optimization strategies for handling simultaneously both, linear and nonlinear impairments of the channel. We apply the algorithms on probabilistically shaped signals transmitted over standard single mode fiber and non-zero dispersion shifted fiber in order to consider conditions in which the system performance is evidently affected by nonlinear phase noise. The results obtained are finally compared to the statistically estimated achievable phase noise removal. This allows to evaluate in different system scenarios an upper bound to the potential gain obtainable by algorithms developed to mitigate the detrimental impact of short-correlated nonlinear phase noise.
Keywords: fiber nonlinearities, nonlinear phase noise, carrier phase recovery, blind phase search.

1. INTRODUCTION

The Kerr nonlinearity of the fiber is one of the main limiting factors for the achievable transmission capacity [1]. The impairment that this effect causes on the propagating signal is often described by an equivalent noise source, referred to as nonlinear interference noise (NLIN). In contrast to the amplified spontaneous emission (ASE) noise, which characterizes the linear channel, NLIN can show a significant amount of phase and polarization rotation noise [2], causing the additive white Gaussian noise (AWGN) channel model to become an unacceptable approximation. This behavior is particularly evident in the case of short reach transmission, low symbol rate and propagation over low dispersion fibers [3], and it is enhanced when high order modulation formats are employed [4]. One can phenomenologically separate NLIN into two components to analyze its statistics: a nonlinear phase noise component (NLPN) and an additive Gaussian noise component, which we call residual noise (ResN) [5]. The adjective *residual*, referred to the Gaussian noise, is chosen because in common dispersion uncompensated scenarios carrier phase recovery (CPR) is able to cancel most of the NLPN, leaving only the ResN component on the constellation after digital signal processing (DSP). Nevertheless, CPR is usually designed for the purpose of cancelling linear phase noise, which arises from the linewidth of the transmitter's laser and of the local oscillator. Blind algorithms allow to maximize the throughput by avoiding time-multiplexed pilot symbols. Among them the blind phase search (BPS) algorithm is a common choice for quadrature amplitude modulated (QAM) signals. A drawback of blind phase estimation is the sensitivity to cycle slips (CS), which can have a destructive impact on the received symbols [6].
In this paper we analyze the achievable mitigation of NLPN by CPR considering the interplay of the nonlinear and linear impairments in defining the optimized parameters of the phase estimation algorithm. We perform this estimation in different transmission scenarios by using as a comparison the signal to noise ratio (SNR) after ideal phase noise compensation obtained through the statistical analysis proposed in [5]. This allows us to understand how much the post-DSP constellation approaches the AWGN model, and thus, what performance gain can be obtained by employing additional mitigation strategies as for example the nonlinear-aware soft-decoding scheme proposed in [3].

2. ANALYZED SCENARIOS

The received complex signals that we analyzed are obtained by simulations using VPIphotonics Design Suite 10.1. Five polarization multiplexed 50 GHz spaced 32 Gbaud signals are simulated around a central wavelength of 1550 nm. At the transmitter the signals are shaped using a raised cosine filter with zero roll-off. The transmitter's laser is characterized by a linewidth of 100 kHz in order to include linear phase noise in the simulation. Probabilistically shaped (PS) 64-QAM with a target entropy of 4.5 is set as the modulation format. The symbols are shaped following a single Maxwell-Boltzmann probability mass function over the entire simulated block length of 2^{16} symbols. PS constellations which approach a Gaussian distribution on the I-Q plane have been found to have stronger NLPN contribution [4,5] and to provide a penalty for the BPS algorithm [7]. We selected this modulation format for our analysis in order to observe conditions in which NLPN is expected to have a significant contribution to the overall system performance. After the transmitter the signals, characterized by a launch power of 0 dBm, are transmitted over up to 20 spans of 80km long fiber. Two fiber types are tested: a standard single mode fiber (SSMF) characterized by attenuation coefficient $\alpha = 0.2$ dB/km, dispersion D = 16 ps/(nm km), effective nonlinear coefficient 1.3 $W^{-1} km^{-1}$ and effective area A_{eff} = 80 μm^2, and a non-zero dispersion shifted fiber (NZDSF) for which the dispersion parameter is changed to D = 3 ps/(nm km). After each fiber span an amplifier characterized by a noise figure NF = 5 dB restores the signal power to its input value. After transmission chromatic dispersion and polarization mode dispersion are perfectly compensated. Finally, the channel of interest (CUT) is filtered, sent to an ideal coherent receiver and CPR is performed.

3. CARRIER PHASE RECOVERY IMPLEMENTATION

In this work we implement CPR by means of a feedforward BPS algorithm [8]. The method is based on rotating the received constellation of a certain number of test phases and to estimate block-wise the test phase for which the distance among the rotated points and their decisions over the ideal constellation points is minimized. The two parameters that can be tuned are the number of test phases N_p and the window size N_w. As for every blind phase estimator one of the main problems is the need to keep the CS probability sufficiently low. The presence of random noise in the constellation enhances the probability of CS so that a larger window size allows for a strong reduction of the CS by providing a more accurate statistics over the estimated symbols in each block [6]. In standard coherent receivers, where CPR is performed to cancel linear phase noise, the simplest approach is to employ a single stage BPS with sufficiently high N_w to provide sufficiently low CS occurrence. This approach, although simple and hardware efficient, performs effectively only when the correlation length of the phase noise is very long. Note however that NLPN may exhibit a correlation length that is much shorter in comparison to what is needed in order to avoid CS – a filter with high number of taps may average out this phase correlation information, and thus deliver a performance penalty. This behavior is particularly evident when employing NZDSF, for low baud rates and for short transmission distance. In fact in all these cases the correlation introduced by the interaction of the different transmitted symbols does not build up efficiently, as explained by the pulse collision theory [2].

For these reasons we test and compare three different CPR implementations: (i) a single stage BPS with fixed window length (SS-FW) using N_w = 50, which proved to be sufficiently long to practically avoid CS in the simulated scenarios; (ii) a single stage BPS with variable window length (SS-VW) in which N_w is optimized to minimize the symbol error rate (SER) and eventually the SNR if no errors are detected; (iii) a dual stage BPS (DS) in which the first stage with N_w = 50 is used to minimize the number of CS and the second stage is optimized to follow the dynamics of the phase noise by minimizing the SNR while avoiding additional CS by comparison with the data provided by the first stage. This last strategy has been proposed in [9] where it was applied to a blind Viterbi-Viterbi phase estimation algorithm.

Although the optimization of the window length is crucial to follow the noise dynamics, the number of test phases N_p plays also a central role in the BPS algorithm. Higher N_p improves the resolution of the algorithm and is able to provide a more accurate phase noise mitigation. This of course comes at the cost of a rapid increase in hardware complexity and power consumption. For this reason, we perform simulations with N_w = 16 to consider an efficient implementation and N_w = 64 to observe the improvement connected to an increased number of test phases.

4. ANALYSIS AND RESULTS

We start by analyzing the case in which transmission takes place over SSMF. The CPR strategies are applied to the same received constellation. Our results (shown in Figure 1) reveal several insights.

First of all, dual stage CPR outperforms the other two proposed schemes in all conditions, with the simple SS-FW CPR providing the worst performance as expected. The ideal phase noise cancellation that is used here as a reference is obtained through the statistical method proposed in [5], based on the second and fourth order moments of the received symbols' amplitude distribution. This method was implemented by exploiting the knowledge of the transmitted data in order to give an ideal theoretical upper bound for the phase noise cancellation. Coming to the CPR implementations the performance penalty among the different solutions is reduced for long-haul scenarios (> 15 fiber spans), where the NLPN is characterized by long temporal correlation and ResN + ASE noise dominate the optimal choice of N_w towards larger values. For this transmission distance also the parameter N_p has a reduced impact, with both tested cases approaching a penalty of 0.5 to 1 dB.

For short transmission distances (< 3 fiber spans), however, where the short accumulated correlation makes CPR less effective, the penalty obtained by using a fixed long window size increases dramatically. As in these cases the accumulated noise is much lower (SNR > 25 dB) the SS-VW scheme performs well using a short N_w without incurring CSs that would degrade the SER. In fact, this allows the SS-VW to approach the performance of the DS CPR. For what concerns the number of test phases, higher N_p is needed to approach ideal PN mitigation by the two schemes based on optimizing N_w. This is due to the larger ratio between the variance of the short-correlated NLPN and the one of the Gaussian noise component, which requires a finer phase estimation in order to approach the constellation obtained after ideal PN cancellation. In this condition, a less hardware intensive approach could be the implementation of an uncorrelated PN aware soft decoding strategy as proposed in [3].

Finally, for medium transmission distance with N_p = 16 similar results to the long-haul case are observed, while with N_p = 64 we clearly observe a region in which SS-VW and DS CPR are able to approach the theoretical phase noise mitigation with less than 0.1 dB SNR penalty. In this condition in fact the correlation accumulated by NLPN is already sufficient for an effective mitigation by means of CPR, and the accumulated ResN + ASE noise is not strong enough to direct the optimum N_w towards excessive values. While this is always true for the DS CPR, the VW-SS CPR is more sensitive to the occurrence of CS and then alternates performance drops ranging from 0.1 up to almost 1 dB in this working region. This is a clear evidence of how the DS CPR is able to combine the best features of the other two approaches, resulting in a much more reliable algorithm.

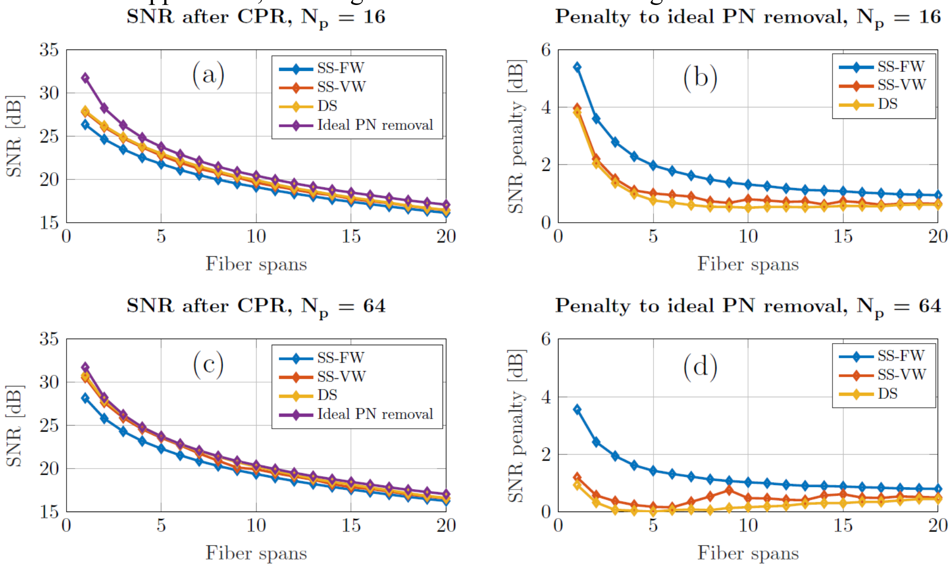

Figure 1. (a,c) SNR after the proposed CPR implementations and ideal phase noise removal, (b,d) SNR penalty of the CPR implementations with respect to ideal phase noise removal. All data for transmission over SSMF.

The same analysis is now performed for transmission over NZDSF, the results are displayed in Figure 2. For this set of simulations similar conclusions to the ones derived for the transmission over SSMF are obtained regarding the relative performance of the CPR schemes. Nevertheless, it is evident that much higher penalties are obtained for medium and long-haul transmission. The lower dispersion in the fiber in fact reduces the interaction among pulses for a given transmission distance and at the same time enhances NLIN, whose ResN adds up to the ASE noise and directs the optimum N_w towards larger values. Clearly the interplay of these two phenomena leads to the rapid drop in the performance observed over the increasing number of spans.

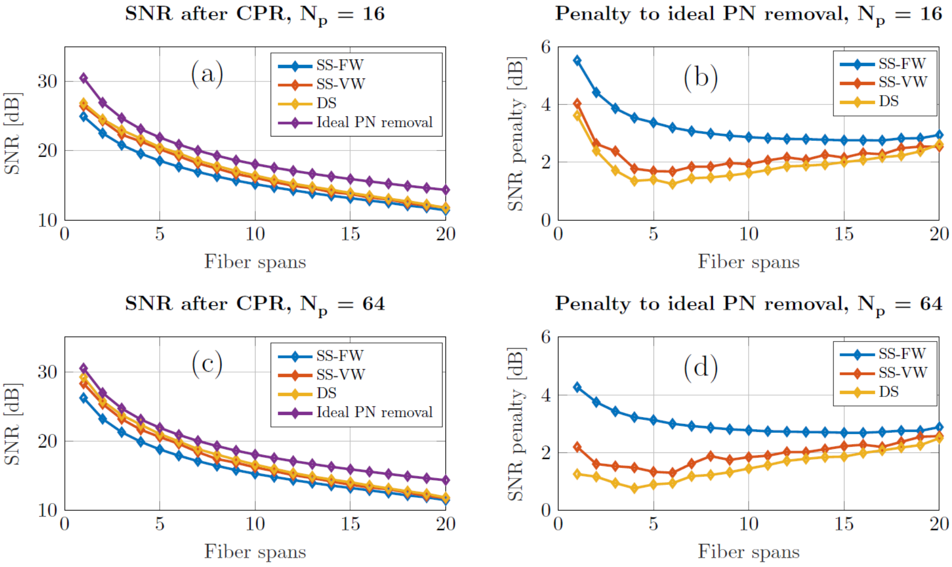

Figure 2. (a,c) SNR after the proposed CPR implementations and ideal phase noise removal, (b,d) SNR penalty of the CPR implementations with respect to ideal phase noise removal. All data for transmission over NZDSF.

Finally it is interesting to understand the relative weight of the NLIN dynamics and of the incomplete mitigation of the linear phase noise on the achievable performance observed with the proposed CPR. This information can in fact provide a quantification of the improvement which is possible to obtain by using additional DSP designed specifically for handling short-correlated NLPN as in [3]. For this purpose we apply DS CPR in the case of a linear channel in which, to perform a fair comparison, the ASE power after each span is properly adjusted to match the whole ResN+ASE power observed in the two cases previously presented after ideal phase noise removal.

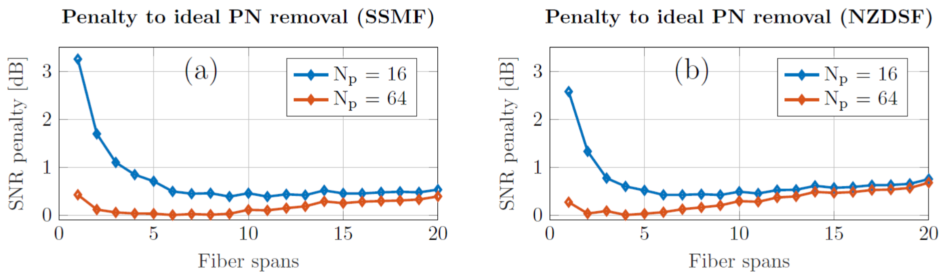

Figure 3. SNR penalty of DS CPR with respect to ideal phase noise mitigation for the equivalent linear channel for transmission over (a) SSMF and (b) NZDSF.

For what concerns SSMF, we obtained similar penalties for long-haul transmission with respect to the ones observed including NLPN (compare Figure 3 (a) with Figure 1 (b,d)). This behavior confirms that in this condition the correlation length of NLPN is long enough such that it can be mitigated well by a CPR utilizing a window size that is large enough to perform optimally considering the accumulated Gaussian noise. Investigating the penalties after the first spans we find again a similar trend between the simulations for $N_p = 16$, demonstrating that the test phase resolution is the limiting factor which introduces a large SNR penalty. On the contrary, for $N_p = 64$ we observe a 0.5 dB lower penalty for the equivalent linear channel after the first fiber span, which implies incomplete mitigation of the short-correlated NLPN. Comparing the results for NZDSF transmission (Figure 3 (b) and Figure 2 (b,d)), we observe an evident decrease of the penalty of over 1 dB with respect to the nonlinear channel cases for all the tested transmission distances, also when 64 test phases are used. This confirms the importance of accounting for incomplete NLPN mitigation when employing NZDSF also for long transmission distances.

CONCLUSIONS

We have explored the achievable level of NLPN mitigation in different transmission scenarios, which are characterized by different amounts of accumulated correlation for the NLIN and Gaussian noise power, introduced either as ASE noise or ResN. The results obtained show that a two stage CPR outperforms single stage solutions by combining resilience to cycle slips while at the same time following better the dynamics of short-correlated NLPN. We compared these results to reference results using the best achievable phase noise mitigation and showed that this solution is feasible only in conditions where the Gaussian noise variance and the phase noise correlation direct the filter length towards a similar optimum. On the contrary, when sufficient temporal correlation is not accumulated by the NLPN an evident penalty of up to 1 dB has been quantified due to incomplete mitigation of the short-correlated NLPN. This value sets an upper bound to the achievable performance improvement that short-correlated NLPN-aware algorithms can provide in the conditions that we analyzed.

ACKNOWLEDGEMENTS

This work is funded by the EU under H2020-MSCA-ITN-2018 Grant Agreement 814276 (WON) and the German Ministry of Education and Research under the grant 16KIS0993 (OptiCON).

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