Machine Learning-Aided Nonlinearity-Tailored Carrier Phase Recovery for Subcarrier Multiplexing Systems

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Abstract: Nonlinear phase noise (NLPN) hampers the benefits of digital subcarrier multiplexing (DSCM) systems. Our paper introduces a low-complexity carrier phase recovery (CPR) method for countering NLPN in DSCM systems, achieving 0.5 dB improvement over conventional CPR.

1. Introduction

Long are the days in which fiber capacity was plenty for our needs, when we did not need to worry about the limits to optical fiber throughput. However, as the demand for greater capacity escalated, fiber nonlinearities have emerged as a relevant domain of investigation within the field of optical communications. As famously modeled by the nonlinear Schrödinger equation, fiber nonlinearities arise from the amplitude-to-phase conversion throughout propagation. The instantaneous amplitude of the signal is converted into a phase rotation, resulting in what is given the name of nonlinear phase noise (NLPN). Due to this conversion, carrier phase recovery (CPR) subsystems are known for partially mitigating fiber nonlinearities [1]. However, in systems affected by chromatic dispersion (CD) this problem becomes more complex. After CD, NLPN is perturbed by phase-to-amplitude conversion, closing the amplitude-phase-amplitude conversion loop that generates the amplitude component of nonlinear interference (NLI). This component cannot be tackled by CPR anymore.

The abovementioned interplay between CD and fiber nonlinearities is what leverages lower over higher baud rates in long-haul fiber transmission, in a phenomenon known as symbol-rate optimization (SRO). In lower-baud rate systems, the latter phase-amplitude conversion might become negligible. With residual intra-subcarrier CD, NLPN becomes the dominant source of NLI, hence making CPR an attractive nonlinearity mitigation solution, with its inherent lower complexity when compared to state-of-the-art nonlinearity compensation algorithms.

Digital subcarrier multiplexing (DSCM) systems enable lower baud rate operation without changing the system's overall bandwidth. However, they pose a challenge w.r.t. CPR performance, as lower baud rates struggle with keeping up good estimates of the phase noise, resulting in poor to no compensation of phase noise if not done properly. In [2], we have addressed the issue of matching the performance of CPR systems regardless of the baud rate, through joint-subcarrier CPR (JCPR). In [3], we present a CPR tailored to the CD, showing that, by adding system-awareness into the CPR design, we can not only match the performance of single-carrier systems but actually even go beyond it. Both in [4] and [5], the authors have, likewise, demonstrated to improve the performance of JCPR in DSCM systems. Namely, in [5], a CPR is derived from the knowledge of the cross-correlation of the NLPN across several subcarriers.

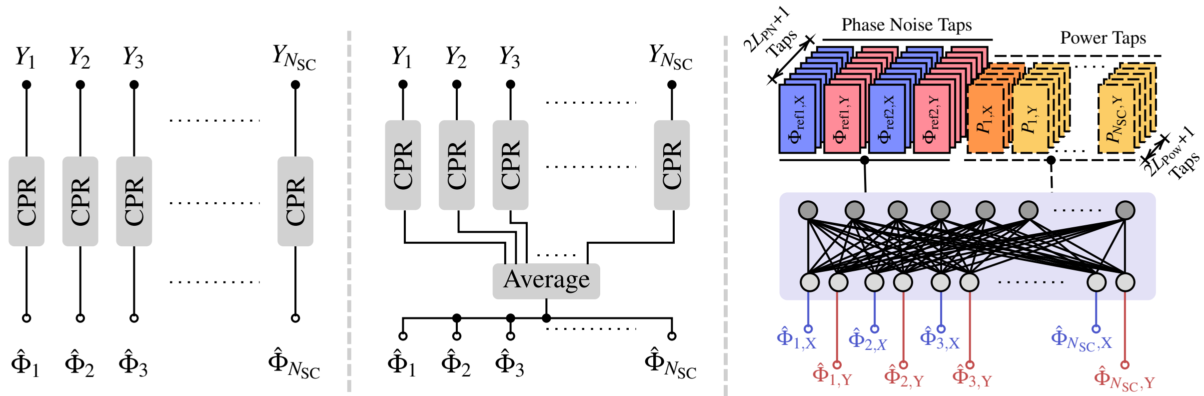
On the question of what other gains can be achieved if the CPR subsystem is educated w.r.t. fiber nonlinearities, in this paper, we present a nonlinearity-tailored CPR (NLT-CPR) algorithm for DSCM systems that is able to over-perform previous contributions to state-of-the-art joint-subcarrier CPE. We assess the performance of this algorithm through numerical simulations, in single-channel and WDM transmission. This analysis is done while keeping in mind and discussing the complexity of the proposed NLT-CPR.

2. Proposed Carrier Phase Recovery Algorithm

In our recently proposed dual-reference subcarrier CPR [3], we combine the phase noise (PN) estimates from two reference subcarriers to enable improved PN correction, by being aware of the chromatic dispersion, and accounting for it in the PN regeneration. In this work, we study the possibility of improving the system-aware regeneration of the PNs through machine learning (ML). Our goal is to have a model that, from the estimated PNs of the two reference subcarriers, can reconstruct the PNs of the remaining subcarriers. For the sake of clarity, in Fig. 1, we present the CPR approaches to be considered in this work: i) a classical per subcarrier CPR (perSC-CPR, Fig. 1a); ii) a naive joint-subcarrier CPR (JCPR, Fig. 1b); and iii) our proposed nonlinearity-tailored CPR (NLT-CPR, Fig. 1c).

The input of our NLT-CPR consists of L_{PN} delayed and L_{PN} advanced taps as well as the present value of the PN estimates of the two reference subcarriers in both polarizations, i.e., 4 input vectors, $\{\Phi_{\mathrm{ref1,X}}, \Phi_{\mathrm{ref1,Y}}, \Phi_{\mathrm{ref2,X}}, \Phi_{\mathrm{ref2,Y}}\}$, each of length $2L_{PN}+1$. Optionally, we can also include an additional input of L_{Pow} delayed and L_{Pow} advanced taps and the present value of each subcarrier's received power, i.e., $2\times N_{\mathrm{SC}}$ input vectors, $\{P_{1,\mathrm{X}}, P_{1,\mathrm{Y}}, \ldots, P_{N_{\mathrm{SC}},\mathrm{Y}}\}$, each of length $2L_{\mathrm{Pow}}+1$. The output of our NLT-CPR is the PN estimate for each subcarrier.

The NLT-CPR is composed of a simple neural network, with a single layer of neurons, with a linear activation function, connecting the inputs to the outputs. Note that one of the benefits of using a machine learning framework,



(a) perSC-CPR (b) JCPR (c) Proposed NLT-CPR(L_{PN},L_{Pow})

Fig. 1: Diagrams of the different compared CPR architectures.

is that we readily have access to complexity reduction tools, such as intelligent pruning of the taps' weights, which allows us to substantially reduce the complexity of the CPR with minor performance degradation.

Training (i.e., tuning) the NLT-CPR was performed on dual-polarization single-channel transmission, for the target distance of 2400 km and, additionally, for an intermediate distance of 1280 km. Except for the number of optical channels, the same simulation parameters were used between training and testing, presented in the next section. The dataset size for training was 196000 samples, split into batches of size 32, and trained for 10 epochs, with the Adam optimizer. In this work, when assessing the performance of the NLT-CPR in the WDM setting, we do so without retraining the weights, to comment on the generalization capability of the method.

3. Numerical Setup

To assess the performance of the proposed NLT-CPR, we have chosen a dual-polarization wavelength division multiplexed (WDM) system, with either single-channel transmission or 5 optical channels (5 WDM). Each channel corresponded to 256 Gbaud DSCM transmission, in a 275 GHz grid. We have fixed our analysis to an optical launch power of 7 dBm per channel. The DSCM system has a number of subcarriers, N_{SC}, equal to 64, corresponding to a subcarrier baud rate of 4 Gbaud. The modulation format was probabilistic constellation shaped 64QAM, with an entropy of 5.5 bits/sym/pol. The link consisted of 30 spans of 80 km of standard single-mode fiber, and was simulated via split-step Fourier method. At the receiver, we performed matched filtering and CD compensation, followed by the assessed CPRs. The compared CPRs work solely based on single-stage pilot-based approaches, with an overall pilot-rate of 1/32, i.e., $\sim$3 %. For NLT-CPR, with all the pilot symbols concentrated on the two reference subcarriers, and having 64 subcarriers, this overall pilot-rate of 1/32 corresponds to having fully data-aided reference subcarriers. The indexes for the references were strategically chosen to be the 16th and 48th subcarriers, located at 1/4 and 3/4 of the spectrum of the channel under test, respectively.

4. Results

The performance of our proposed NLT-CPR is compared against the lower and upper bounds for CPR. The lower bound is the simple per-subcarrier CPR (perSC-CPR), using a pilot-aided algorithm. On the other hand, the upper bound for performance is a data-aided CPR (DA-CPR), which assumes that all transmitted symbols are known at the receiver, and ideal PN compensation is performed. For completeness, we have also added as a comparison the performance of a joint-subcarrier CPR (JCPR).

We start the analysis of the results with Figs. 2a and 2b. In these figures, we plot the SNR gain of the different studied CPRs against a simple constant phase rotation of the received constellations. These results are shown for single-channel transmission. For Fig. 2a, the proposed CPR was tuned for a distance of 1280 km, whereas for Fig. 2b it was tuned for the target distance of 2400 km. We see that, at this low baud rate, perSC-CPR is not able to provide any gain over a simple constant phase rotation. The NLPN has far less memory than the one required by the perSC-CPR to filter out noise in the PN estimates. This is what drives the need for the proposal of advanced CPR algorithms for DSCM systems. The naive JCPR can bring some performance gain over the constant phase rotation, but this gain is limited to $\sim$0.1 dB at the target distance of 2400 km. By better distributing the pilot allocation, and from learning the NLPN behavior, our proposed NLT-CPR(64,0), with $L_{PN} = 64$ and $L_{Pow} = 0$, can increase the CPR gain to 0.3 dB, despite using the same information (phase noise alone and the same overall pilot-rate). Since CPR is desired to have low complexity, we can resort to complexity reduction tools such as pruning the unnecessary weights to reduce the complexity of the CPR. Resorting to pruning, we managed to reduce the complexity of our NLT-CPR(64,0) by over 98% with a negligible performance penalty, from 1032 real multiplications per subcarrier $(4\times2\times(2L_{PN}+1))$ to an average of 15 real multiplications per subcarrier. The performance of this pruned network is shown in Figs. 2a and 2b under the label NLT-CPR(64,0), and we can verify that pruning the weights of the network w.r.t to the phase delay taps results in a negligible penalty.

Afterward, we wanted to assess if further CPR improvement was possible if the CPR is aware of the instantaneous power received in the several subcarriers. To this end, in Figs. 2a and 2b, we also assess the performance of NLT-CPR(64,15), with $L_{PN} = 64$ and $L_{Pow} = 15$, in which the CPR was trained not only using as input the NLPN estimated in the two reference subcarriers but also the instantaneous power measured. Note that this power can be obtained without overhead on the transmitted signal. Adding the information of instantaneous power alone, the

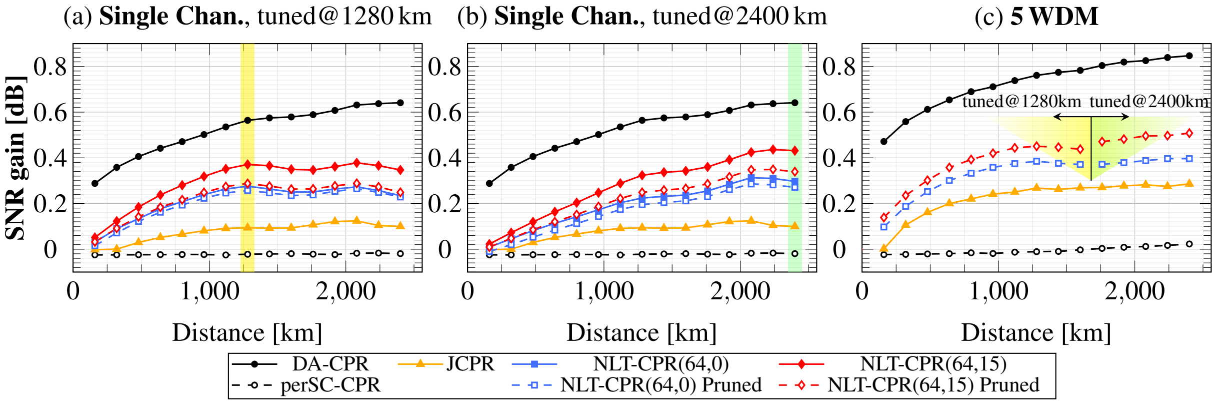


Fig. 2: Results for 256 GBaud 64SCs at a launched power per channel of 7 dBm. We compare the proposed NLT-CPR with other CPR alternatives. The results are presented for single-channel transmission, with weights tuned to (a) 1280 km and (b) 2400 km; and for (c) 5 WDM transmission.

NLT-CPR can now learn how power fluctuations affect the NLPN, and although the added information is blind to the phase, we were able to improve PN estimation and further extend the gain of the NLT-CPR by another 0.1 dB, achieving a total gain of 0.4 dB over conventional CPR, or 0.3 dB over a naive JCPR. We remarkably observe that our proposed NLT-CPR allows to reduce the gap between realistic CPRs and ideal CPR, going from a gap of 0.5 dB with a naive JCPR to a gap of only 0.2 dB with our NLT-CPR(64,15). Resorting again to pruning, and imposing the same complexity reduction of 98%, for NLT-CPR(64,15), we reduced the number of real multiplications per subcarrier from 8968 to a per ubcarrier average of 180. However, we can observe that the NLT-CPR with power terms is much more sensitive to pruning than when we had PN terms alone, with pruning resulting in loss of most of the performance gain over NLT-CPR(64,0). This can be attributed to the fact that, while the L_{PN} taps were more redundant, the L_{Pow} taps have greater relevance and less redundancy in their role to compensate for NLPN. Regarding the difference in performance between tuning the NLT-CPR for 1280 km or 2400 km, it is noteworthy that this difference seemed minor. The difference in SNR is always within 0.1 dB. However, as expected, training at 1280 km was better for short distance and 2400 km better for larger distances.

Finally, to test the generalization of our proposed NLT-CPR, and to test its performance in a scenario closer to a practical implementation, we have tested the CPRs tuned for the single-channel in a 5WDM transmission scenario, without retuning. We can see the results of this test in Fig. 2c. For this scenario, since we are not interested in highly complex solutions, we show only the results for the pruned NLT-CPRs. Even though the pruned NLT-CPR(64,15) led to little performance advantage over NLT-CPR(64,0) in the single channel scenario, for 5 WDM we still observed the benefit of having the power input in NLT-CPR. For distances of up to 1600 km, the NLT-CPR tuned for 1280 km led to better performance, while for longer distances the weights tuned for 2400 km performed better. In the WDM scenario, although the weights were not specifically tuned for it, NLT-CPR(64,0) still shows an SNR gain of 0.1 dB over naive JCPR, and adding the power inputs, to the NLT-CPR(64,15), we got an extra gain of 0.1 dB, totaling up in a gain of 0.5 dB over the conventional perSC-CPR. Even in a mismatched scenario of 5 WDM, our proposed NLT-CPR allowed us to reduce the gap between realistic CPRs and ideal CPR, going from a gap of 0.6 dB with a naive JCPR to a gap of only 0.3 dB with our pruned NLT-CPR(64,15).

5. Conclusion

While the study of advanced CPR algorithms tailored for fiber nonlinearities is far from complete, this work sheds light on how there is room for novelty in CPR for low baud rate systems, bringing us a step closer to unleashing the benefits of SRO. In this work, we have shown how simple manipulation of the phase noises measured in two subcarriers can give us better NLPN compensation than naive averaging of the phase noises among all subcarriers. Also, allowing the CPR to have overhead-free information on the received power on all subcarriers can further improve NLPN compensation. A 0.5 dB SNR improvement over conventional CPR has been achieved whilst limiting the system's complexity.

6. Acknowledgments

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