Experimental Demonstration of Nonlinear Sequence Selection for Single- and Multi-Carrier WDM Coherent Systems

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Abstract *We conduct the first experimental validation of the nonlinear sequence selection technique, for a 17x110 Gbaud DP-PCS-64QAM system. Similar SNR gain of 0.2 dB is measured for single-carrier and 8-subcarrier signals after 1360 km transmission, showing nonlinear gain even in the presence of CPR.*
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Introduction

The topic of nonlinear shaping has recently been the target of extensive research in the scientific community. Several works have reported how tuning the block-length of the probabilistic constellation shaping (PCS) matcher can minimize fiber nonlinearities [1]–[4]. This is because its length imposes a constraint on the statistics of the transmitted signal. However, to effectively benefit from this approach, we face a compromise between the nonlinear gain of decreasing the block-length of the distribution matcher and the associated linear penalty caused by rate loss. Furthermore, these nonlinear gains vanish if carrier phase recovery (CPR) is employed[5].

Recently, a new nonlinear shaping technique named *sequence selection* has surfaced [6],[7]. This technique involves two steps. The first step is generating a myriad of candidate fixed-length dual-polarization (DP) symbol sequences, propagating them numerically through a noiseless fiber, and ranking them based on the generated nonlinear interference (NLI). The second step is selecting a pre-defined percentage of the best-performing sequences, by imposing an *acceptance rate*, and these accepted sequences are the ones used for the actual propagation.

While this technique initially surfaced with the goal of achieving a new lower bound for the capacity of the optical channel, it clearly also holds potential for nonlinear shaping. Faced with the reality that the technique—as described above—consists of an unpractical approach for real systems, practical implementations for this technique have been recently proposed[8]–[10]. However, all the reported results so far are only based on purely numerical studies, and it is thus important to experimentally validate the actual benefit of nonlinear sequence selection in a real system. Furthermore, it is also crucial to assess the impact of CPR on the nonlinear gains provided by sequence selection, which was not taken into account in previous works featuring this technique.

Considering a 17-WDM 110 Gbaud dual-polarization (DP) PCS64QAM system, in this paper, we conduct the first experimental validation (to the best of our knowledge) of practical SNR gains (∼0.2 dB) enabled by nonlinear sequence selection, which is performed at a fixed distance over a digital twin of the actual fiber link, and then experimentally applied to a wide range of transmission distances with both single-carrier and subcarrier-multiplexing signals.

Implementation of Sequence Selection

For the numerical selection of sequences, we followed a strategy similar to the one originally proposed in[6]. First, we conducted noiseless single-(sub)carrier split-step Fourier method (SSFM) simulations, emulating propagation of a DP-PCS64QAM signal, sampled from a Maxwell-Boltzmann (MB) distribution, with an entropy of 5.5 bits/sym/pol. Propagation is performed over a fixed distance corresponding to 24 spans of 100 km of standard single-mode fiber (SSMF). Then, we parsed the signal into blocks of 256 4D symbols, and selected the 256 symbols-long DP sequences that led to the least generated NLI noise. The impact of inter-sequence interference on selection is mitigated by averaging the same block with different interfering sequences prior to selection. The selection is performed separately for the two different baudrates.

Experimental Setup

The experimental setup is shown in Fig. 1. We used three different transmitters to create the WDM channel interferers and the channel under test (CUT). For the channel under test, we generate a 110 Gbaud PCS64QAM signal using a digital-to-analog converter (DAC) operating at 130 Gsample/s. The signal entropy is 5.5 bits/sym/pol. The remaining channels are cre-

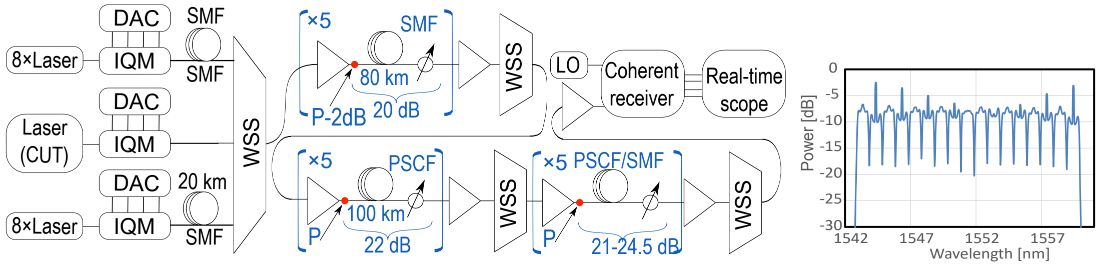

Fig. 1: (left) Experimental setup. (right) Transmitted spectrum consisting of 17×110 Gbaud channels.

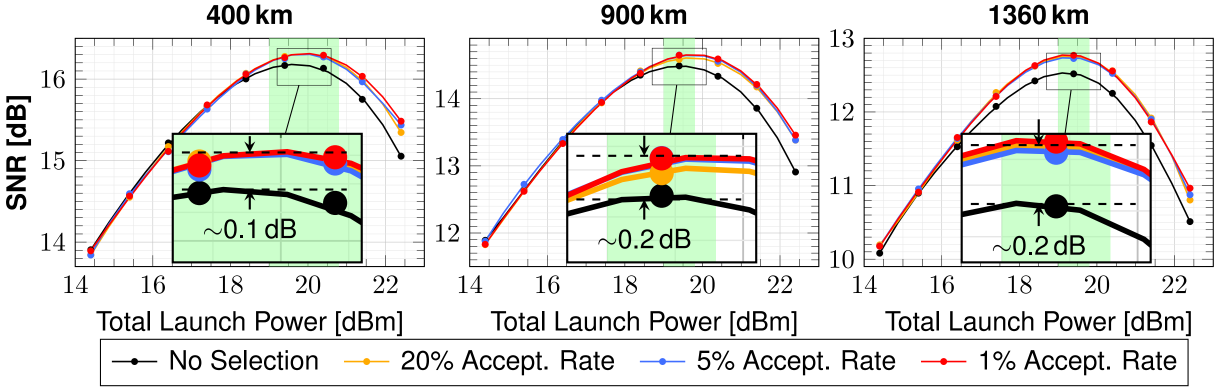

Fig. 2: SNR vs. total launch power for single-carrier and different distances.

ated by inputting 8 laser waves into the other two transmitters. The signal created by these other transmitters is similar to the CUT, 110 Gbaud with 5.5 bits/sym/pol. When assessing sequence selection, the three transmitters share the same pool of sequences, but they are chosen in random order for each transmitter. Additionally, to evaluate the impact of the baudrate, we made use of SCM to be able to apply sequence selection at 110 (single-carrier) and 13.75 Gbaud (8 SCs). The outputs of the three transmitters are combined using a wavelength-selective switch (WSS) to form the WDM signal shown in Fig. 1. For the interferer channels modulated on the same transmitter, we use 20 km of SSMF fiber to decorrelate them.

The WDM signal is then launched into the transmission link, which consists of three sections of five spans each. The fiber type varies according to the section, with single-mode fiber (SMF) in the first section, pure silica core fiber (PSCF) in the second one, and both SMF and PSCF in the third section. The span loss is adjusted by a variable optical attenuator (VOA) to be 20 dB, 22 dB, and between 21 and 24.5 dB for the first, second, and third sections, respectively. In between sections, we use WSSs to compensate for EDFA ripples and tilt.

At the receiver, the CUT is filtered before being mixed with the local oscillator in a coherent receiver. After sampling the electrical signals, we perform offline digital signal processing (DSP) including chromatic dispersion compensation, adaptive equalization, and carrier frequency and phase recovery. For the CPR we use two stages, the first is a pilot-aided CPR, which is performed jointly in the SCM scenario[11], and the second is a finer blind decision-directed/maximum-likelihood (DD-ML) stage.

Experimental Results

First, we analyze the SNR performance of the CUT after each section (400, 900, and 1360 km). These results are displayed in Fig. 2, where we see the SNR performance of single-carrier transmission for the different distances, and, at each distance, for different acceptance rates (100%, 20%, 5%, and 1%). It is observed that, albeit using the (same) selected sequences that were numerically obtained for a fixed 24×100 km SSMF link, gain is observed regardless of the link length, indicating thus that, as one could expect, sequences that have been selected for a particular distance show good nonlinear performance even outside the distance of selection. The observed gain of sequence selection is in the order of 0.2 dB for the assessed distances. However, for 400 km, the gain is mainly impaired by transceiver noise, and we only attained a gain of 0.1 dB. Note that while these gains could be arguably contained within experimental error, the fact that the trends are smooth regardless of the launch power, indicate that these gains are real and not experimental error. Another notable remark stemming from Fig. 2 is that even an acceptance rate as high as 20% suffices to attain the majority of the nonlinear gain at the optimum launch power.

In Fig. 3, we present the nonlinear gains provided by sequence selection at 1360 km for

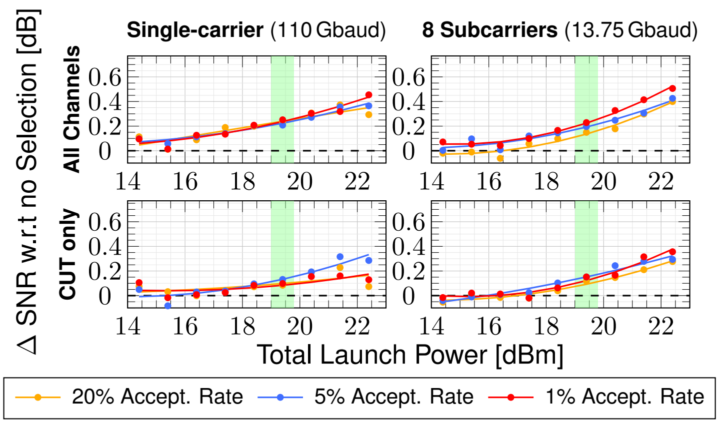

Fig. 3: SNR gain vs. total launch power at 1360 km for (left) single-carrier and (right) 8 subcarriers, where the green region indicates the optimum launch power. (top) All WDM channels using sequence selection. (bottom) Only CUT with sequence selection.

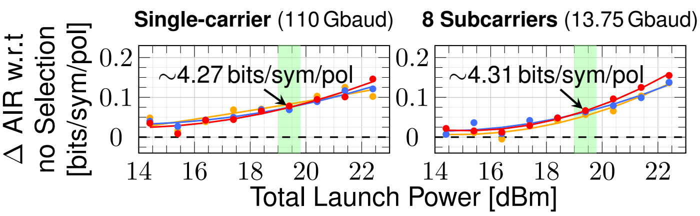

Fig. 4: AIR vs. launch power at 1360 km for (left) single-carrier and (right) 8 subcarriers, with optimum launch power shaded in green. Selection on all channels.

single-carrier, in the left column, and for 8 subcarriers, in the right column. We show two different scenarios: i) the top row, where all channels use the same modulation format, subcarrier number, and percentage of sequence selection as the CUT; and, ii) the bottom row, where the WDM neighbors are single-carrier signals with the same modulation format but without selection. These results have as baseline the signal at the corresponding baudrate, but with no selection, which allows to decouple symbol-rate optimization (SRO) from actual nonlinear shaping gains.

i) Impact of Baudrate per (sub)-Carrier: In the top row of Fig. 3, we can see a nonlinear gain of roughly 0.2 dB at the optimum power for both baudrates. Therefore, we experimentally show that sequence selection gains can be kept reasonably constant regardless of the baudrate.

ii) CUT-only versus Full-WDM Selection: In Fig. 3, the bottom and top rows show different trends depending on the baudrate. For high baudrate systems, sequence selection provides practical gains through both intra- and inter-channel compensation. To fully benefit from sequence selection in these systems, all channels should implement nonlinear shaping. Conversely, for low baudrate systems, sequence selection across all WDM channels only slightly improves overall performance, while CUT-only selection preserves most of the achievable nonlinear shaping gain. Note that these conclusions were drawn for per-subcarrier selection, and they may not hold true for joint selection, which, however, would require unrealistically large complexity and very wideband super-channels.

Finally, in Fig. 4, we analyze the potential impact of the rate loss incurred by selection, which may affect the achievable information rate (AIR) even if SNR gain is present. This rate loss is generally negligible for reasonable acceptance rates, and is given by $-\log_2(\eta)/2N$ [6], where η is the acceptance rate and N is the block size (256 in our scenario). This translates into a loss of 0.005, 0.008, and 0.013 bits/sym/pol for 20%, 5%, and 1%, respectively. This AIR loss incurred by a smaller acceptance rate cancels its marginal SNR performance advantage, further emphasizing that an acceptance rate of 20% is enough to enjoy the benefits of sequence selection at the optimum launch power. Nevertheless, for the maximum assessed launch power, there was still some benefit of a 1% acceptance rate, even with the additional rate loss. The abovementioned SNR gain of ~0.2 dB thus translates into an AIR gain slightly over ~0.06 bits/sym/pol, which is in line with the numerical results in[6]. Regardless of the similar AIR gain for the different baudrates, we see that they lead to different absolute values of AIR, namely 4.27 for single-carrier and 4.31 bits/sym/pol for 8 subcarriers. This difference can be mainly attributed to SRO gains[11], and thus emphasizes how the gains of sequence selection and SRO are additive.

Conclusions

In this paper we have experimentally demonstrated for the first time that nonlinear sequence selection can provide gain for i) different distances and ii) low and high baudrates. The observed gain is about 0.2 dB or 0.06 bits/sym/pol and it can be attained with an acceptance rate of 20%. Larger sequence selection (i.e. smaller acceptance rate) only provides noticeable gain when operating beyond the optimal launch power. Note that these gains are achieved in spite of having realistic CPR in the receiver DSP. Additionally, we have also shown that the gain is mainly due to intra-channel nonlinear compensation. Further sequence selection gain could be achieved by joint sequence selection across the several subcarriers, and/or by performing the selection of the sequences directly over the practical system.

Acknowledgments

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