Experimental Validation of Sequence-Wise Predistorter for Evaluation of Geometrically Shaped 128-QAM

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Abstract: A predistorter for transmitter nonlinearities is applied to the evaluation of a geometrically shaped constellation, such that constellation points are transmitted correctly during the evaluation of the geometrically shaped constellation. © 2022 The Author(s)

1. Introduction

As the need for higher per channel capacity continues to grow in optical transmission systems, baud rate and constellation cardinality are increasing. Hence more stringent requirements are placed on the transmitter in terms of bandwidth and linearity of the driver amplifiers and Mach-Zehnder modulator [1, 2]. Recently, constellation shaping via geometric shaping (GS) has been demonstrated to increase the capacity per channel even further [3]. For GS, the precise transmission of constellation points is especially important, since GS constellation points are chosen carefully such that they result in a Gaussian-like profile. Various methods have been proposed to overcome transmitter limitations. A precompensation technique for low electrical bandwidth [4] and a Volterra series based nonlinear predistortion method [1] have been presented, as well as a less complex memory polynomial based predistorter [5]. In [6], a more easy to implement lookup table (LUT) based method was proposed.

In this work, a sequence-wise (SW) predistortion method is demonstrated for the evaluation of GS-128-QAM and is compared to a LUT based method proposed and demonstrated in [6]. For evaluation of GS constellations, mitigation of the constellation point shift due to nonlinearities is important, as otherwise the designed GS constellation is not optimally tested. Hence, the maximum performance might not be achieved. Significant performance increase over only linear precompensation is shown, and the SW method is shown to outperform the LUT predistortion for practical table sizes. Due to the SW nature of this method, the predistorter needs to be trained for every transmitted sequence and hence, it is noted that technique is not suitable for application to real-world transmission systems. However, for constellation design and transmission evaluation, this remains a valuable tool, since transmitter impairments will have less influence during experimental validations.

2. Sequence-wise predistortion

The SW predistorter is based on [6]. There, a LUT is created for each dimension (i.e. XI, XQ, YI, YQ) where a pulse-amplitude modulation signal is sent. The LUT contains the amplitude errors for the center symbol of each possible symbol pattern with length $n$. The LUT is filled by transmitting and receiving a pseudorandom bit sequence (PRBS) in an optical back-to-back (OBTB) setup as described in Section 3, downsampling the resulting signal to 1 sample per symbol, identifying the $n$-length patterns, and calculating the errors for the center symbol. If a pattern occurs more than once, the error is averaged. Increasing the LUT pattern length $n$, the amount of memory effects the LUT can capture increases, at the cost larger table sizes. To apply the symbol-wise LUT at the transmitter, the amplitude of each symbol is corrected using the pattern-dependent error stored in the LUT.

For the sequence-wise (SW) predistorter, the pattern length $n$ is set equal to the length of the transmit sequence, justifying the name of the predistorter. The LUT will be able to capture memory effects as long as the transmit sequence and will contain as many non-zero entries as there are symbols in the transmit sequence. However, a certain LUT is only valid for the same sequence as it was trained on. Using the same LUT structure as in [6] would not be feasible, as the LUT size is given by the number of possible symbol patterns $L^n$, where $L$ is the number of output amplitudes in a single dimension. Note that as each pattern in the LUT occurs only once, the errors for the SW method can be stored in a LUT with the same size as the transmit sequence. Since each pattern occurs only once in the transmitted sequence, the noise is not averaged out as for a LUT with a short pattern length. Therefore, the LUT of the SW method is trained iteratively. The LUT is filled and used to re-transmit the sequence, then, again errors are determined and added to the values which are already in the LUT.

Fig. 1: (a) Experimental setup (b) Original and received constellation points. (c) Simulated NGMI vs. SNR
The predistortion method is validated using the setup in Fig. 1a. PRBSs containing 2^{16} GS-128-QAM symbols are generated at 48.8 Gbd, predistorted for nonlinear effects, root-raised-cosine shaped with 1% roll-off, precompensated for linear transmitter bandwidth limitations and uploaded to a digital-to-analog converter (DAC). The 193.4 THz tone produced by an external cavity laser is modulated by a dual-polarization IQ-modulator and transmitted over 75 km of single-mode fiber (SMF). At the receiver, the signal is received by a coherent receiver, after which it is digitized, followed by coherent receiver digital signal processing. For OBTB measurements, the components in Fig. 1a denoted by Optional for single span are left out of the setup. At the transmitter, noise-loading is achieved by filtering the amplified spontaneous emission of an erbium-doped fiber amplifier.

In Fig. 1b, the GS-128-QAM constellation, optimized as described in [3], is shown. Fig. 2a depicts the normalized generalized mutual information (NGMI) when transmitting this constellation using only linear precomp for different output swings of the DAC. Higher swings are associated with higher transmitter optical signal-to-noise ratios (OSNRs), but with more transmitter nonlinearities. As seen from Fig. 2a, the maximum NGMI occurs at 400 mV, for which the received constellation points are given in Fig. 1b. The points are shifted and compressed, resulting in worse maximum performance. This is simulated in Fig. 1c, where additive white Gaussian noise is added to both the original GS-128-QAM constellation and the distorted one. A penalty of 0.02 in NGMI can be observed between the original and the distorted constellation, indicating that without predistortion, the tested GS constellation is not the same as the designed one.

The SW method is compared with the LUT predistortion method for a short pattern length. Due to the non-uniform placement of the constellation points for the GS-128-QAM constellation, the number of possible amplitudes levels is not 12 as for 128-QAM, but 36. Hence, increasing the pattern length above 5 results in extremely large LUTs (∼ 300 × 10^9 entries for n = 7) and therefore only n = 3 and n = 5 are evaluated. In Fig. 2c, the NGMI vs. OSNR is presented for a DAC output swing of 400 mV. A NGMI forward error correction (FEC) limit of 0.85 is also depicted in Fig. 2c, corresponding to a 540 Gb/s net data rate [7, 8]. It can be seen that only the SW predistorter and the LUT method with n = 5 achieves the FEC limit. The received constellations with and without the SW predistorter are shown in Fig. 2b. The NGMI vs. DAC output swing for the SW predistorter is given in Fig. 2a. It can be seen that the decrease in NGMI when increasing the driving voltage is lower when compared to the only linear precompensation case, resulting in the ability to increase the OSNR after the modulator.

4. Conclusions

A SW predistorter to compensate for the transmitter nonlinearities, aimed at design and evaluation of advanced modulation formats, where the correct transmission of constellation points is especially important, is presented. The SW method is easier to implement and train, and is shown to outperform existing LUT based methods for practical table sizes for the evaluation of a geometrically shaped 128-QAM.

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