Extremely Accurate (0.1dB) Nonlinear Distortion Characterization of Optical Transmitters Using Spectrum Analyzer Only

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Abstract *Through a novel design method for test signals, we revive a convenient nonlinear distortion characterization method that has been impractical for 50 years for optical communications. An 0.1 dB accuracy is achieved using a spectrum analyzer only. ©2023 The Author(s)*

Introduction

As the data rate per wavelength increases from 100Gbps to 400Gbps, 800Gbps, or even beyond, nonlinear distortion in optical transmitter would become dominant factor to limit the transmission reach. In open network scenarios, the transmitted signal quality should be specified in a measurable form to guarantee multi-vendor interoperability. Thus, accurately, and practically assessing the transmitter nonlinearity is a fundamental but challenging problem for our community [1]. It becomes even more complicated if nonlinear digital pre-distortion (DPD) is used.

The fundamental difficulty in this problem resides in a fact that the nonlinear distortion depends not only on the nonlinear characteristics of a device, but also on the stochastic characteristics of the signal to be transmitted, such as the probability distribution function (PDF) and peak-to-average power ratio (PAPR) [2]. Noise power ratio (NPR) method imposes spectral notch(es) in the signal to be sent, and measures the regrowth of spectrum component induced by the nonlinearity at the output of the nonlinear device. This method is very simple and has been widely used to measure the nonlinear distortion for Gaussian stimuli [3] since its proposal in 1971 [4]. However, many optical communication systems have non-Gaussian stimuli, such as pulse amplitude modulation (PAM) or quadrature amplitude modulation (QAM). For non-Gaussian stimuli, the notch operation that introduces long-term memory inter-symbol-interference, changes the PDF to a Gaussian function, and then increases the PAPR and nonlinear distortion [5]. As a result, the measurement is not accurate anymore. In some extreme cases, such inaccuracy can be as much as 8 dB [6]. In [7], we proposed the probability-maintained (PM) NPR method to address this issue. However, it needs full programmability of the input symbol pattern and thus conflicts with the pre-defined pilot symbols in open communication systems [8].

In this paper, we solve this problem by an enhanced algorithm. The basic idea is to find a special symbol pattern that has a frequency notch by manipulating the payload symbols, while maintaining the pre-defined pilot symbols and the same PDF as those of actual communication systems. We use an unaccompanied optical spectrum analyzer to evaluate the nonlinear distortions of a 64QAM transmitter with 11 nonlinear conditions and the performance of 9 nonlinear DPD types with various complexities. The correlation coefficient R^2 between the generalized signal to noise ratio (GSNR) and the Q factor is 0.99, and the root mean square error (RMSE) of the Q factor estimation is 0.1 dB.

Basic concept of the NPR method, PM notch signal, and GSNR

The conventional NPR method utilizes a signal with a narrow notch band as the stimulus, as shown in Fig. 1 (a). Then, the spectral regrowth component in the output is considered the in-band nonlinear distortion component because linear effects will not generate any new frequency component. However, the notch operation changes the PDF, then the nonlinear distortion measurement is not accurate anymore [5]. As a comparison, the PM NPR method uses a specially designed symbol pattern as the stimulus, which not only contains a frequency notch but also has the same PDF as that of actual communication system, as shown in Fig. 1 (b) and (c). The PM notch signal is also a symbol sequence, hence the nonlinear distortion is not changed by the notch. Furthermore, the PM NPR method is also applicable to DPD because DPD should accommodate any input symbol pattern. Finally, the GSNR, which is defined as the ratio

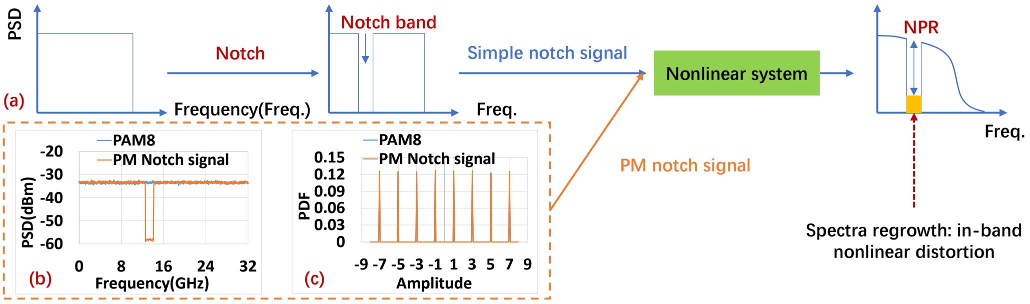


Fig. 1: (a) Schematic of the conventional NPR method, (b) the spectrum and (c) the PDF of a PM notch signal. PSD: power spectrum density

between the signal power and the power sum of nonlinear distortion and the additive noise, is used to estimate the Q factor.

Improved search method for PM notch signal

A practical communication system uses pre-defined pilot symbols, e.g., the quadrature phase shift keying (QPSK) pilot inserted every 32 symbols [8], as shown by the frame structure in Fig. 2 (a). If the input symbol pattern is freely designed, a notch depth of 25 dB is achieved for PAM8, which is the I or Q tributary of the 64QAM format, as shown in Fig. 2 (b) [7]. However, it conflicts with the requirement of pre-defined pilots. Two straightforward methods that can accommodate this requirement are a) inserting the pilot symbol in the searched sequence and b) replacing the searched symbol by the pilot symbol at the pilot positions. Fig. 2 (b) shows that

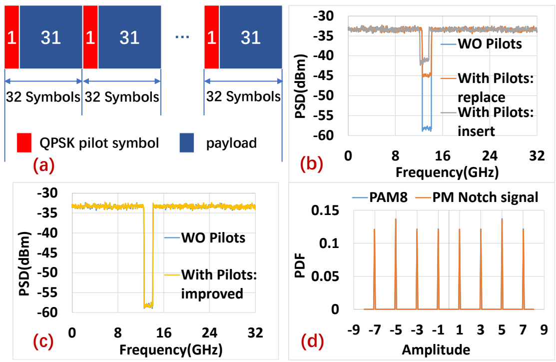


Fig. 2: (a) The frame structure used in this study, the spectrum of the PM notch signal with pilot symbols realized by the (b) straightforward methods and (c) improved method, and (d) the PDF of the PM notch signal and normal communication signal with QPSK pilot symbols.

both methods fail, and the notch depths are only 13 dB. The reason is explained as follows. A frequency notch indicates a long correlation in the time domain, and either directly inserting or replacing the pilot symbols destroys this correlation.

To solve this problem, we fix the pre-defined pilots in the searching process, as shown in Fig. 3. The key is Step1: construct PDF based on the "kept order criteria". After Step1, the iterated signal is replaced by the reference samples that have the desired PDF so that the probability is maintained. The "kept order criteria" means that the replacement operation does not change the order. For example, supposing the iterated signal has the maximum value (b[19]) at time index 19, then the replaced sample at time index 19 is the maximal one of the reference samples (a[2]). In the improved method, the iterated signal at the pilot position is replaced by the pre-defined pilot symbol first. Then, the iterated signal at the payload position is sorted and replaced by the reference samples. Since the ratio of the pilot symbol is just 1/32, and the payload is replaced based on the "kept order criteria", the spectrum should not be significantly changed. Step3 achieves the notch but may change the PDF. After iterations, the PM notch signal with pre-defined pilot is expected. Step2 adjusts the fine structure within the resolution bandwidth but keeps the overall spectrum beyond the resolution bandwidth. It is necessary to escape from local optima during iterations. For more details, please consult Ref. [7]. Fig. 2 (c) shows that the notch depth of the improved method also reaches 25

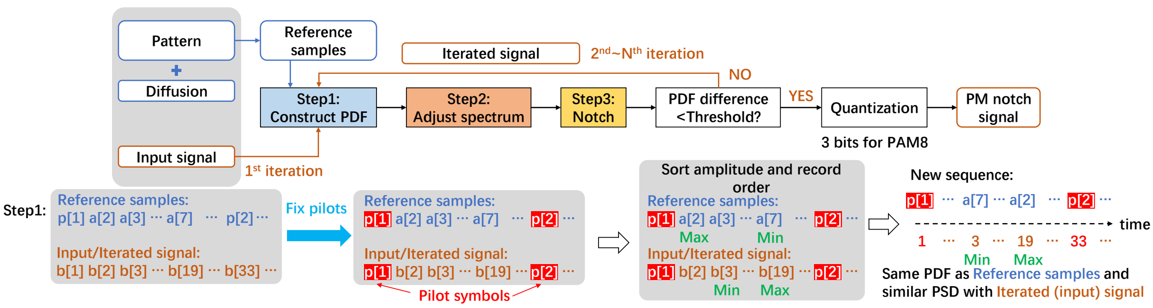
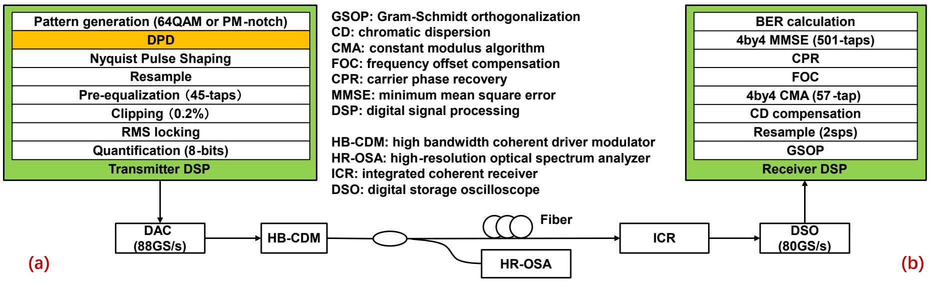


Fig. 3: Principle of the improved search method for PM notch signals with pre-defined pilot symbols.



DPD scheme	Memory length
DPD off	-
Volterra1	[35 3 1]
Volterra2	[35 5 3]
Volterra3	[35 11 7]
Volterra4	[35 15 13]
Volterra5	[35 15 13 9 7]
Volterra6	[3 3 3]
Volterra7	[5 5 5]
Volterra8	[7 7 7]
LUT	3

Fig. 4: (a) Experimental setup of the unamplified system with 10-km transmission and (b) the memory length and order of different DPD schemes.

dB. The PDF of the searched sequence is shown in Fig. 2 (d), where the higher PDF at symbol +/- 5 refers to the QPSK pilots.

Experiment verification

Fig. 4 (a) shows the experimental setup of a 10 km unamplified transmission system, where the transmitted signal is 64 Gbaud 64QAM with Nyquist pulse shaping (roll-off factor = 0.15). Linear pre-equalization is used to compensate for the filter response of the digital-to-analog (DAC) and high bandwidth coherent driver modulator (HB-CDM). HB-CDM is the main nonlinear distortion source. Two experimental scenarios are considered in this study: 1) changing the nonlinearity conditions with disabling the DPD; 2) changing the DPD schemes with fixing the nonlinear condition. For the first one, the root mean square (RMS) of DAC's input signal with full swing of -127 to 127 is swept from 17.2 to 54.4 to emulate 11 different nonlinear conditions. For the latter, 9 DPD schemes of different complexity are evaluated with a fixed signal RMS of 43.2. Fig. 4 (b) shows the memory length information about the test DPD schemes, including the 3-order and 5-order Volterra series as well as the look up table (LUT) [9]. Taking Volterra1 as an example, 35, 3 and 1 refer to the memory lengths of the 1st-, 2nd-, and 3rd-order nonlinearities, respectively. The high-resolution optical spectrum analyzer (HR-OSA) measures the in-band nonlinear noises at 6 different frequencies by the improved PM notch signals that contain 1.6 GHz notch bandwidth. The receiver employs conventional digital signal processing. In addition, the strength of additive noise is calibrated in the experiment.

Fig. 5 (a) and (b) displays some exemplary spectra measured by the improved PM NPR method for the experiment without and with DPD, respectively. The I and Q tributaries have the same notch frequency and notch bandwidth but have different symbol patterns. As a result, the optical spectrum has a symmetrical notch in positive and negative frequencies. Fig. 5 (c) shows the Q factor versus the GSNR averaged over the 6 notch frequencies for both experimental scenarios. The experiments include 11 nonlinear conditions and 9 nonlinear DPD schemes. The correlation coefficient R^2 is 0.99, and the RMSE of the estimated Q factor according to the linear fitting line is as low as 0.1 dB. Fig. 5 (c) also shows the theoretical Q values, which are very close to the experimental values. The slight difference can be attributed to the imperfections in the receiver except the additive noise.

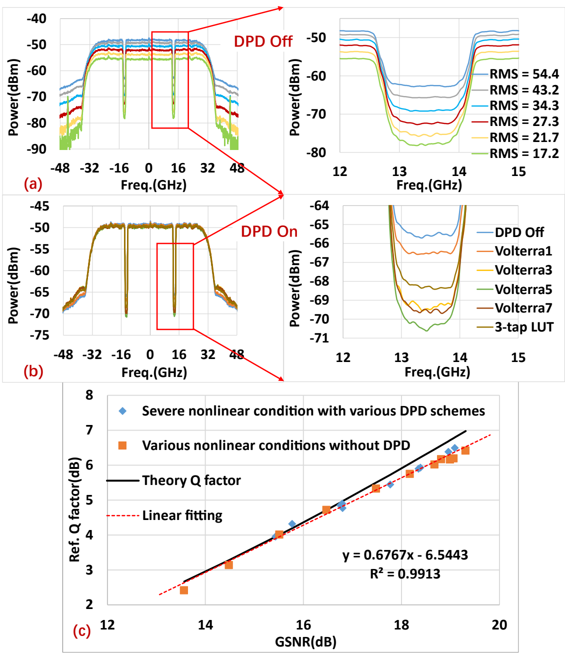


Fig. 5: Spectra measured by the PM NPR method for (a) various nonlinear conditions without DPD and (b) severe nonlinear condition with various DPD schemes, (c) the reference Q factor and theory Q factor versus the measured mean GSNR

Conclusion

We experimentally verify a convenient and extremely accurate assessment method for both the nonlinear distortion and the performance of DPD. It accommodates the requirement of pre-defined pilot symbols in practical systems. A correlation coefficient R^2 of 0.99 between the Q factor and the GSNR is achieved. The RMSE of the Q factor estimation is as low as 0.1 dB. We believe that the proposed method will revive the 50-year-old NPR method.

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