Characterization of Linear and Nonlinear Impairments in Optical Coherent Transmitter Using Probability-Maintained Notch

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Abstract *We propose an enhanced probability-maintained notch method for complex signal, such as 32QAM. With this method, the nonlinear distortion and IQ imbalance in optical coherent transmitter could be distinguished using a spectrum analyzer. ©2023 The Author(s)*

Introduction

In the open network scenario, the transponders of different vendors should interoperate. Thus, the transmitted signal quality, including the linear and nonlinear characteristics, should be specified [1]. For IM-DD system, such quality can be characterized using a reference receiver [2]. However, similar approach has not reached an agreement for coherent system. Meanwhile, the linear and nonlinear impairments are not easy to be distinguished using such approach.

Noise spectrum measurement is a practical and effective method to estimate the transmitter quality. The in-phase/quadrature (IQ) imbalance of a coherent transmitter could be measured by comparing the spectrums of single- and dual-side simple notches [3]. If the input signal is Gaussian, the nonlinear distortion could be characterized by noise-to-power ratio (NPR) [4, 5] measured by dual-side simple notch which is defined as the power ratio of the regrowth component at notch region to the nonlinear output. For pulse amplitude modulation (PAM) or square quadrature amplitude modulation (QAM) which is composed of two independent PAMs, we have proposed real-valued probability-maintained (PM) notch, which not only achieves dual-side notch but also keeps the probability distribution function (PDF) of the stimulus, to correctly measure the nonlinear distortion in optical coherent transmitter

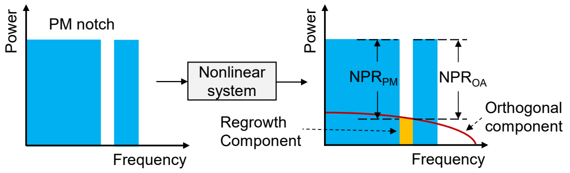

Fig. 1: Schematic of NPR measurement.

[6]. Fig. 1 illustrates that NPR measured by PM notch agrees with that measured by orthogonal analysis (OA) which is defined as the power ratio of orthogonal component to nonlinear output at notch region [6]. However, single-side PM notch and the PM notch for 32QAM still lacks because the real-valued PM notch proposed in [6] needs "sorting" operation and it cannot be used for complex signal.

In this paper, we propose an enhanced PM notch method for the complex signal. Then, we experimentally verify that the nonlinear distortion and IQ imbalance could be separated by a spectrum analyzer, where the dual-side PM notch measures the correct nonlinear distortion and the spectrum difference between the single- and dual-side PM notches indicates the IQ imbalance.

PM notch for complex signal

Fig. 2(a) shows the flow of PM notch generation for PAM. The initial input signal has a Gaussian PDF, and the reference samples are PAM pattern with a small random diffusion. The reference samples have the desired PDF. Each iteration

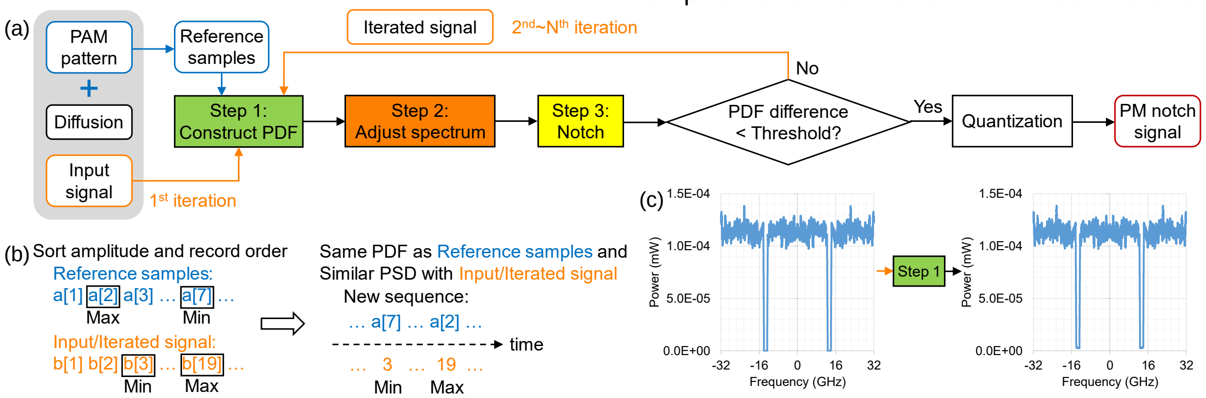

Fig. 2: (a) Flow of PM notch for PAM, (b) detail of step 1, and (c) spectrums of iterated signal before and after step 1.

includes three steps. In step 1, the input/iterated signal is replaced by the reference samples while the amplitude order is maintained as shown in Fig. 2(b). For example, the amplitude at time index 3 is always the minimum one before or after replacement. It is apparent that the new sequence has the desired PDF. In addition, the power spectrum density (PSD) is not significantly changed by the replacement because the amplitude order does not change. Fig. 2(c) shows an example. In short, step 1 achieves the desired PDF and does not significantly affect the PSD. Step 3 is the conventional band-stop filter. It achieves the desired PSD but may change the PDF. With the iteration of step 1 and step 3, the PM notch signal could be expected. Step 2 only adjusts the fine structure within the resolution bandwidth of PSD, and it is necessary to escape from the local optima [6].

Step 1 is the key process in the generation of PM notch signal. In the case of complex signal, such as 32QAM, we still have the reference samples composed of ideal 32QAM constellation plus a small random diffusion. We could still replace the input/iterated signal by the reference samples so that the desired PDF (i.e., the I-Q two-dimensional joint PDF) is achieved. The question is how to avoid the significant PSD change during the replacement. We cannot use the "kept order criterion" for complex signal because complex signal cannot be sorted.

We propose a new replacement criterion based on sequential sorting. The reference samples a[n] are generated from ideal 32QAM constellation so that we could easily classify the reference samples into 32 red groups $r^a_{I,Q}$ where $I, Q \in [-5, -3, -1, 1, 3, 5]$, e.g., $r^a_{3,5}$ shown in Fig. 3(a) means the group of the samples generated from constellation 3+j5. We also classify the reference samples into 6 green groups g^a_Q based on the imaginary values only, e.g., g^a_5 shown in Fig. 3(a) means the group of the samples generated from the constellation with imaginary value equals 5. After classification, we could count the number of reference samples in each red or green group.

For each input/iterated signal b[n]=I+jQ, based on the amplitude order of imaginary value, we find which green group g^b_Q it belongs to, e.g., guaranteeing the number of input/iterated signal in g^b_5 shown in Fig. 3(b) equals that of reference samples in g^a_5. Then, we find the corresponding red group $r^b_{I,Q}$ based on the amplitude order of real value within each green group, e.g., guaranteeing the number of input/iterated signal in $r^b_{3,5}$ shown in Fig. 3(b) equals that of reference samples in $r^a_{3,5}$. Till now, we found the

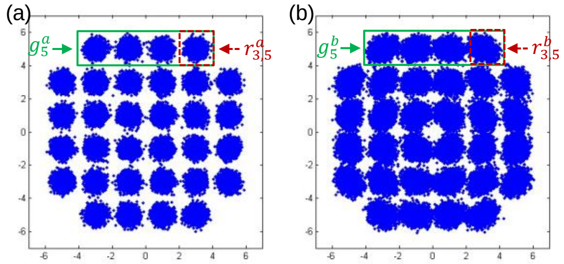

Fig. 3: Constellations. (a) Reference samples and (b) iterated signal.

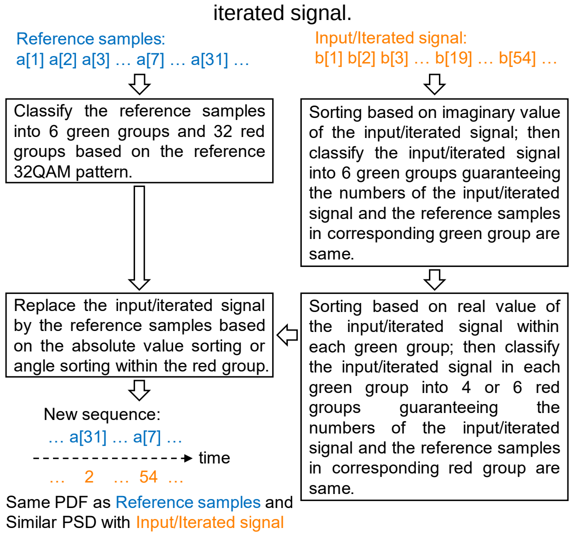

Fig. 4: Detail of step 1 of PM notch for 32QAM.

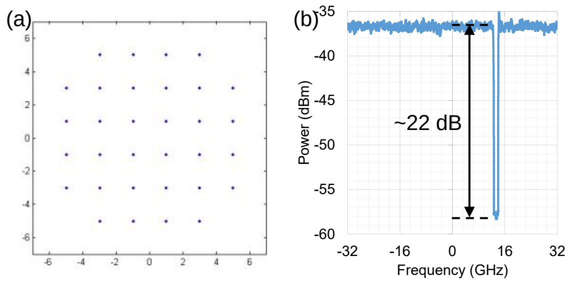

Fig. 5: (a) Constellation and (b) spectrum of single-side PM notch signal for 32QAM.

corresponding red group (or 32QAM constellation) of input/iterated signal b[n]. If we randomly select the reference sample a[n] to replace the input/iterated signal b[n] within the red group, the replacement error will not exceed the distance between two adjacent constellations and the PSD will not change significantly. To reduce the replacement error further, we could replace the input/iterated signal b[n] by the reference sample a[n] based on the absolute value sorting or angle sorting within the red group.

Employing the replacement criterion based on sequential sorting as mentioned above (also shown in Fig. 4) and the same step 2 and 3 as conventional PM notch process (shown in Fig. 2(a)), we find the single-side PM notch signal for 32QAM as shown in Fig. 5. The constellation and the I-Q two-dimensional joint PDF of the single-side PM notch signal are same as that of the reference 32QAM pattern. ~22 dB notch depth is achieved for noise spectrum measurement.

Experimental setup and result

The experimental setup and digital signal processing (DSP) flow for coherent transmitter characterization is shown in Fig. 6(a). The 64 Gbaud 32QAM with or without simple/PM notch is used as test signal. The digital IQ imbalance emulator including IQ amplitude imbalance and IQ skew are loaded after pulse shaping with 0.15 roll-off factor. We do not consider IQ phase imbalance because it is automatically compensated by auto bias controller in high bandwidth coherent driver modulator (HB-CDM). And the inherent linear impairment in transmitter is digitally compensated. Fig. 7(a) shows the optical spectrum with single-sideband modulation and without digital IQ imbalance. ~28 dB single-sideband suppression ratio means the inherent linear impairment is well compensated so that the digital IQ imbalance is the actual imbalance.

The dominant nonlinearity in transmitter is caused by the electrical driver in HB-CDM. The root mean square (RMS) of the digital signal is swept to change the level of nonlinear distortion. The optical spectrum of HB-CDM output $y(t)$ is obtained using a high-resolution optical spectrum analyzer (HR-OSA), and the NPR is measured by simple or PM notch. Note that the finite depth of PM notch signal shown in Fig. 5(b) should be calibrated out in the optical spectrum measurement [6]. Besides, we could capture the waveform of $y(t)$ using integrated coherent receiver (ICR), digital storage oscilloscope (DSO), and DSP, and then the reference NPR is measured by OA shown in Fig. 6(b). The correlated component $y_c(t) = \sum g_k x(t-k)$ is the best linear approximation of the nonlinear output $y(t)$ [7], where $x(t)$ is the waveform after pulse shaping and g_k is the tap coefficient of a 1001-tap 4x4 minimum mean square error (MMSE) filter to minimize $|y(t) - y_c(t)|^2$. Orthogonal component is the rest $y_o(t) = y(t) - y_c(t)$, which can be considered as a nonlinear distortion [7].

Fig. 7(b) shows the dual-side and single-side PM notches. The depth difference is caused by the IQ imbalance in transmitter where 2 dB IQ amplitude imbalance and -2 ps IQ skew (noted as [2 dB, -2 ps]) are loaded. Fig. 7(c) demonstrates

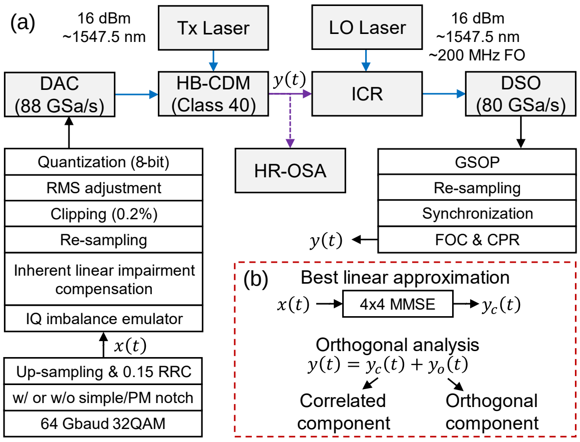

Fig. 6: (a) Schematic of experimental setup and DSP flow, and (b) orthogonal analysis and best linear approximation.

the NPRs at different notch frequencies in the case of RMS of 54.6 and IQ imbalance of [0 dB, 0 ps]. The NPRs measured by dual-side PM notch agree with that measured by OA, i.e., the dual-side PM notch correctly measures the nonlinear distortion. However, the NPRs measured by conventional dual-side simple notch overestimates the nonlinear distortion significantly, which is consistent with our previous results [6]. Fig. 7(d) demonstrates the mean NPRs of different notch frequencies in the case of RMS of 27.3 and different IQ imbalance. It is clear that dual-side PM notch only measures the nonlinear distortion even though the IQ imbalance exists. With the increasing of IQ imbalance, the NPR difference between single-side PM notch and dual-side PM notch increases. The nonlinear distortion and IQ imbalance are distinguished.

Conclusions

We achieve single- and dual-side PM notches for 32QAM enabled by the enhanced PM notch process for complex signal. Experiments show that the nonlinear distortion and IQ imbalance in optical coherent transmitter are separated using a spectrum analyzer. Dual-side PM notch correctly measures the nonlinear distortion even if the IQ imbalance coexists. The spectrum difference between single- and dual-side PM notches is caused by the IQ imbalance.

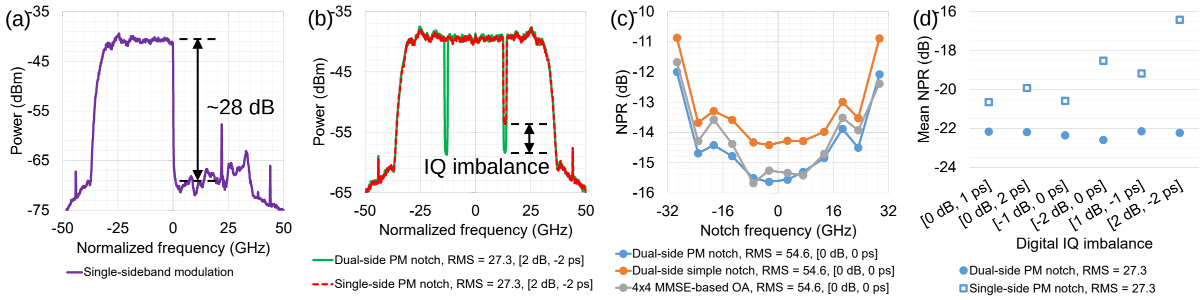

Fig. 7: Experimental results. (a) Optical spectrum of single-sideband modulation, (b) optical spectrums of PM notches, (c) NPRs at different notch frequencies, and (d) mean NPRs in different IQ imbalance cases.

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