How to Connect Device Nonlinear Specification and System Nonlinear Penalty

Zhenning Tao[1*], Ke Zhang[1], Chengwu Yang[1], Xiaofei SU[1], Tong Ye[1], Hisao Nakashima[2], and Takeshi Hoshida[2]

1. *Fujitsu R&D, IFC Tower A 8F, NO. 8 Jianguomenwai Ave, Chaoyang District, Beijing, 100022, * taozn@fujitsu.com*
2. *Fujitsu Ltd., 1-1 Shin-ogura, Saiwai-Ku, Kawasaki 212-8510, Japan*

Abstract: From system design point of view, it's required to estimate nonlinear system performance from device nonlinear specification. We discuss various technologies about this topic and find the problem is only partially solved. © 2022 The Author(s)

1. Introduction

With the increase of network traffic, optical communication uses higher order modulation and higher baud rate. In such system, the transceiver device imperfection turns more and more significant. In addition, the major traffic occurs in metro and data center network where the transmission impairment, such as fiber nonlinear Kerr effect, is less significant than the impairment of transceiver device imperfections. The linear imperfections can be specified by the linear transfer function and IQ imbalance, whereas the nonlinear imperfections are much more challenging [1].

From system design point of view, it's required to estimate nonlinear system performance from device nonlinear specifications. Having such estimation, the system nonlinear penalty could be calculated straightforwardly. There have been various device nonlinear specifications, such as total harmonic distortion (THD), inter-modulation ratio, nonlinear noise to power ratio (NPR), orthogonal components and so on. The challenge here is nonlinear behavior not only depends on nonlinear device itself, but also depends on input signal [2]. The transmitted signal in real communication is usually different from the test signal in nonlinear specification measurement. Thus, it is not easy to estimate nonlinear system performance from nonlinear device specifications.

In this paper, we review several technologies about how to connect device nonlinear specification and nonlinear system performance. In some cases, nonlinear system performance can be accurately estimated from NPR, but we still lack a universal solution to estimate nonlinear system performance accurately and practically.

2. Device Nonlinear Distortion and Specification in Optical Communications

Optical transceiver contains many devices, and most of those devices could be the source of nonlinear impairments. Fig. 1 (a) shows various nonlinear impairment sources in a typical optical coherent transceiver. Both digital to analog converter (DAC) and analog to digital converter (ADC) have integral nonlinearity. Driver and transimpedance amplifier (TIA) have nonlinear effect. The Mach-Zehnder modulator has inherent sin(x) characteristic which is nonlinear in the case of large swing.

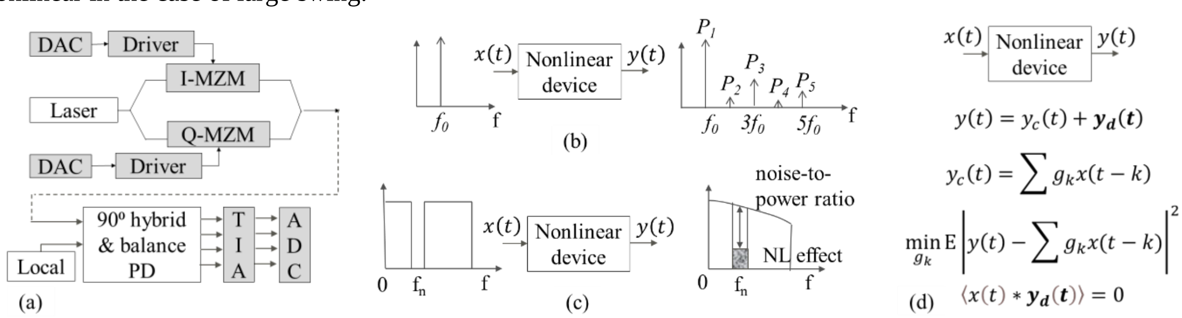

Fig. 1 Device nonlinear impairment and nonlinear specifications (a) Impairment sources in optical coherent transceiver. DAC: digital to analog converter, MZM: Mach-Zehnder modulator, TIA: transimpedance amplifier, ADC: analog to digital converter (b) Definition of total harmonic distortion (c) Definition of nonlinear noise-to-power ratio (d) Definition of correlated component $y_c(t)$ and orthogonal component $y_d(t)$.

There are several specifications of device nonlinear impairments. Fig. 1 (b) shows the definition of THD. A single tone with frequency f_0 is injected into the device under test, and all orders of harmonic tone are measured at output. THD is defined as $\sqrt{P_2 + P_3 + P_4 + \cdots}/\sqrt{P_1}$. Fig. 1 (c) shows the definition of nonlinear noise-to-power ratio. At input, the component of notch frequency f_n is blocked. Due to the nonlinear effect, there is regrowth component at frequency f_n at output, and the ratio between regrowth component and signal power is noise-to-power ratio [3]. Fig. 1 (d) shows the concept of correlated component and orthogonal component which is widely used in wireless [4]. The nonlinear device output $y(t)$ is considered as the summation of correlated component $y_c(t)$ and orthogonal component $y_d(t)$. Correlated component is the best linear approximation of nonlinear system, i.e., $y_c(t) = \sum g_k x(t-k)$ and the coefficient g_k satisfies $\min_{g_k} \mathrm{E}|y(t) - \sum g_k x(t-k)|^2$. Orthogonal component is the left part $y_d(t) = y(t) - y_c(t)$, and the correlation between $y_d(t)$ and $x(t)$ is zero, i.e., $\langle x(t) * y_d(t)\rangle = 0$.

3. Connection between Nonlinear System Performance and Device Nonlinear Specification

Above nonlinear specifications describe the nonlinear characteristic from different aspects. However, communication system cares about BER or Q value. It is necessary to build a bridge between device nonlinear specification and nonlinear system performance. A good bridge should satisfy two requirements: 1) the nonlinear system performance could be estimated at certain accuracy, 2) the specification could be measured practically.

3.1 Equivalent Additive Noise Model for Nonlinear System

Nonlinear distortion is a deterministic effect, which means the distortion depends on the input signal bit pattern. This causes many difficulties in system performance estimation. To solve this issue, we use equivalent additive noise model as shown in Fig. 2, to estimate the nonlinear system performance. The model approximates the nonlinear device by an equivalent linear part and an equivalent additive noise. The nonlinear impairment is described by the equivalent additive noise, and such noise is independent on input signal bit pattern. For different nonlinear specifications, the methods to estimate the equivalent additive noise are different, and the system performance estimation accuracy could be different also. To focus on nonlinear effect, we assume the receiver has ideal linear compensation, such as minimum mean square error (MMSE) equalizer with sufficient tap number.

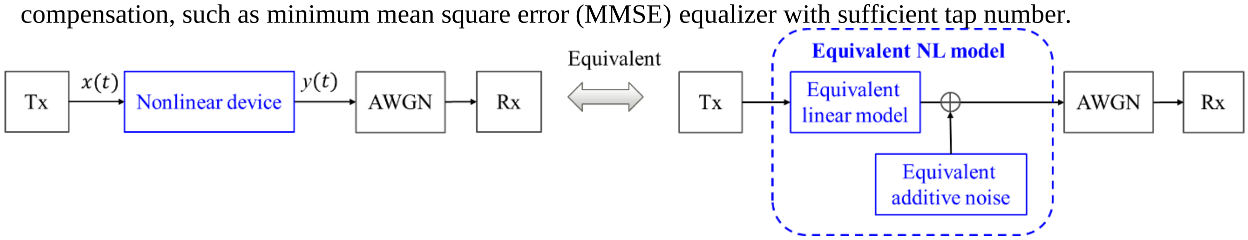

Fig. 2 Equivalent additive noise model for nonlinear device

3.2 Total Harmonic Distortion and Nonlinear Terms

In THD, the nonlinear term is considered as nonlinear distortion. Thus, it is straightforward to consider nonlinear term as the equivalent additive noise. The first drawback of THD is the limitation of low input frequency. If the nonlinearity is frequency independent, the low frequency limitation is not an issue. However, the wide band device in optical communication has strong nonlinear frequency dependency. For example, [5] shows that the high frequency nonlinear distortion is 40dB higher than low frequency one in one commercially available coherent receiver. Thus, THD is not a good nonlinear specification for wide band optical communication device.

Secondly, the nonlinear term cannot be always considered as equivalent additive noise. The experiment of driver in optical coherent transmitter shows that the Q estimation error is as large as 2.6dB if nonlinear term is considered as equivalent additive noise [6]. The reason is the nonlinear term contains the information of input signal. Taking the very basic 3rd order polynomial model $y = x + c_3x^3$ as an example, the nonlinear term is c_3x^3, and the correlation between nonlinear term and input signal is $\langle x * c_3x^3\rangle = c_3\langle x^4\rangle \neq 0$. Thus, part of nonlinear term is the signal itself. Fortunately, [6] also shows the even order nonlinear term could be considered as equivalent additive noise.

3.3 Orthogonal Components

Orthogonal component is the part of nonlinear device output whose correlation to input signal is zero. In other words, orthogonal component cannot be described by any linear process of input signal. Thus, it could be considered as equivalent additive noise naturally. In [6], the Q estimation error of same orthogonal model is less than 0.2dB for the wide band driver in optical coherent transmitter. The high estimation accuracy has also been verified in wireless communication [4].

The drawback of orthogonal component is the difficulties in measurement. It needs coherent comparison of nonlinear device input $x(t)$ and output $y(t)$. This usually requires very expensive instruments such as high-speed arbitrary waveform generator and high-speed digital storage oscilloscope. In fact, if we have output $y(t)$, we could calculate system Q directly. In addition, the orthogonal component $y_d(t)$ is the small difference between two large signals $y(t)$ and $y_c(t)$. Any small measurement error of $y(t)$ and $y_c(t)$ may cause large error in $y_d(t)$.

In optical coherent communication, orthogonal component analysis is trickier. The selection of orthogonal component analysis method depends on the selection of receiver equalizer. In optical coherent transmitter, the major nonlinear distortion is caused by driver and modulator. It occurs separately for I and Q branch. In coherent receiver, there are two kinds of equalizer, i.e., single-input-single-output complex-valued equalizer (1by1 complex) and two-input-two-output real-valued equalizer (2by2 real). Similarly, the orthogonal component analysis also has two options, i.e., 1by1 complex-valued MMSE (OA1) or 2by2 real-valued MMSE (OA2). Fig. 3 shows the system performance estimated by same orthogonal model. The system is 44G baud 64QAM single polarization back-to-back system. If the equalizer uses 1by1 complex equalizer, the selection of orthogonal component analysis does not make sense. If the equalizer uses 2by2 real-value one, the orthogonal component analysis should also be 2by2 real-value.

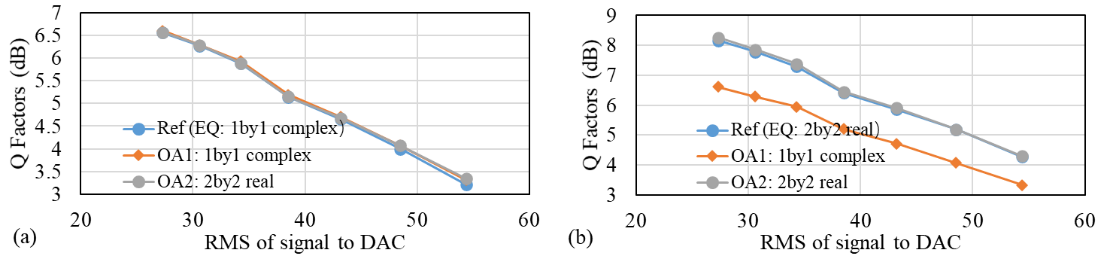

Fig. 3 System performance estimated by the same orthogonal model in optical coherent communication (a) receiver uses 1by1 complex-valued equalizer and (b) receiver uses 2by2 real-valued equalizer.

3.4 Nonlinear Noise to Power Ratio

The big advantage of NPR is that it could be measured much easier compared with orthogonal component. However, NPR does not agree with the orthogonal component and the actual nonlinear noise in general [7]. The reason is that the notch process changes the characteristic of input signal, then the nonlinear behavior changes. If the input signal is Gaussian distribution, the correct nonlinear noise can be measured by NPR [8].

More interestingly, if the dominant nonlinear distortion is 2^{nd} order nonlinearity, the notch process does not change the orthogonal component. Fig. 4 (a) shows the experimental result of 25Gbaud PAM4 VCSEL IM/DD back-to-back system where the dominant nonlinearity is 2^{nd} order one. It's clear that measured NPR describes the spectrum of orthogonal component correctly. Fig. 4 (b) is the simulation result of 2^{nd} order polynomial system and Fig. 4 (c) shows that of 3^{rd} order polynomial system. It's clear that NPR correctly measure the orthogonal component in 2^{nd} order nonlinear system, but not in 3^{rd} order polynomial nonlinear system.

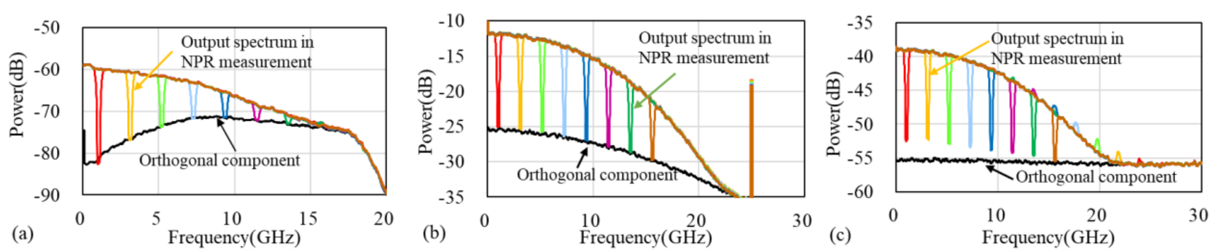

Fig. 4 Orthogonal component and the spectrum of NPR measurement in different nonlinear systems where input signal is 25Gbaud PAM4 (a) experimental VCSEL IM/DD system (b) 2^{nd} order polynomial system by simulation (c) 3^{rd} order polynomial system by simulation

4. Conclusion

Device nonlinearity turns to be the major impairment in high order, high baud rate optical communication system. To estimate nonlinear system performance from device nonlinear specification, various technologies have been developed. The orthogonal component has high estimation accuracy, but it is hard and tricky to be measured. The NPR is easy to be measured, but it does not correctly estimate nonlinear impairment in general. In the case of Gaussian input signal or 2^{nd} order dominant nonlinear system, NPR works correctly.

5. References

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