Low-Complexity RMS-enhanced Digital Pre-emphasis under Limited Transmitter Power and ENoB

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Abstract: We optimize digital pre-emphasis for narrow optical filtering using the balance among electrical RMS, equalization-enhanced noise and quantization, and experimentally show a low-complexity cutoff approach to enhance SNR in strong pre-emphasis.

1. Introduction

The next-generation high-speed optical coherent transceivers suffer from transmitter (Tx) impairments such as limited bandwidth (BW), noise from RF chain, limited digital-to-analog converter (DAC) resolution and limited power to avoid saturation (or Tx nonlinearity) [1]. The electrical responses of XI, XQ, YI and YQ (called S21) should be compensated to mitigate intersymbol interference (ISI). A linear equalizer at receiver (Rx) DSP equalizes ISI caused by Tx S21, but enhances the electrical and link noise simultaneously. On the other end, digital pre-emphasis (DPE), enhancing high frequency content, increases signal's peak-to-average power ratio (PAPR) and reduces its root mean square (RMS) (or power), which eventually degrades the available signal-to-noise ratio (SNR) [1-3].

Partial DPE has been shown to further optimize back-to-back (B2B) performance [3]. The end-to-end (E2E) performance can also be enhanced by particle swarm optimization [4] or MMSE [5], jointly optimizing pre- and post-equalization under transceiver's BW and effective number of bits (ENoB) limitation. However, this does not visualize the underlying causes of SNR degradation. A recent work [6] suggests that a full DPE for Tx S21 is preferred for noisy link, while 50%-DPE for the Tx-noise dominating case, based on a theoretical SNR optimization. However, it over-generalizes the practical scenarios especially under limited RMS and ENoB. For instance, DPE for very sharp S21 roll-offs shrinks RMS and worsens quantization. Thus neither 50% nor 100% DPE could achieve the optimum, but 70% in [7] while 40% in [8]. As wideband transceiver BWs are usually enhanced by peaking technique [2, 9], the tight filtering in the optical links having multiple reconfigurable optical add-drop multiplexing (ROADM) nodes becomes a dominate source of ISI. Other than the link noise [1], it is of our interest to investigate how the DPE behaves under a peaking-enhanced wideband Tx S21 profile (shown in Fig. 2b) and narrow optical filtering.

In this work, we start off from visualizing a phenomenological interplay among equalization enhanced noise, RMS, and quantization, to show that limited ENoB drives DPE away from strong compensation region (<50% DPE). A digital SNR optimizer is used to minimize clipping and driver nonlinearity throughout this work. We experimentally demonstrate a low-complexity cutoff method to enhance signal's RMS without sacrificing the benefits of strong DPE, and conclude that neither 50 % nor 100 % DPE could achieve the optimum mentioned in [6].

2. Background

To quantify the DPE strength, the "*n*th root" approach was used as a DPE filter model for optimization [6]: the *n*th root of the S21 frequency response, $H_{DPE}(f) = 1/H_{Tx}^{\beta}(f)$. This facilitates us to tune the "DPE strength" (as well as PAPR and RMS) by varying β between zero and one. There are mainly two opposing factors to be considered due to DPE. First, a weak Tx-DPE (small β) requires a strong Rx-post equalization to reduce the overall ISI. The high-frequency noise is thus enhanced, called the post-equalization enhanced noise (PEEN). A stronger DPE thus reduces PEEN, as shown in Fig. 1a (yellow dashed line). Second, a stronger DPE leads to a higher PAPR, reducing electrical RMS and thus SNR [2-3] (green dashed line). In case of very sharp roll-off, a strong DPE further reduces SNR caused by over-clipping and nonlinearity. Substantially shrinking RMS avoids these penalties, but quantization kicks in (blue dot-dashed), pushing optimal β towards zero, presented as the "RMS+ENoB-limited case" in Fig. 1b.

To illustrate the quantization effect in a very tight filtering condition, Fig. 1c shows the simulation example of the DPE of 69GBaud DP-16QAM for an ISI channel using an 8^{th}-order super Gaussian filter shape with FWHM at 69GHz×0.9 for various ENoBs. As the ENoB decreases, quantization degrades SNR in the strong DPE region where RMS is small. In practice, ENOB is lower than 5, and thus this result helps us discard all DPE filters with β larger than 0.5. Equivalent speaking, a sharp S21 roll-off turns the Tx into a "power-limited (or RMS-limited) scenario": The optimal β is below 0.5, i.e. $\beta < 0.5$, or the weak DPE region.

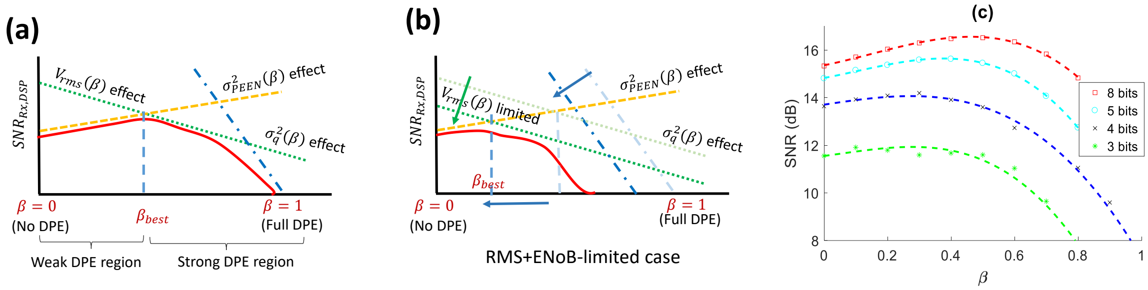

Fig. 1. (a) The three main contributions to determine SNR under Tx constraints (b) RMS and ENoB-limited scenario (c) Simulated impact of quantization effect in the presence of tight filtering on SNR versus β, EDFA gain = 22dB, noise loading at receiver

To avoid over-clipping effect and driver nonlinearity, a digital SNR optimizer is used at TxDSP: After each β-DPE, the resulting waveform, x_t, is multiplied with a digital gain factor, g. The optimal digital gain is $g_{op,dB} = \max_{g}\left\{\langle\, |x_t|^2 \rangle / \left\langle \left| \frac{Q(gx_t)}{g} - Q(gx_t) \right|^2 \right\rangle \right\} - M_{dB}$, where $Q(\cdot)$ is a 8-bit quantization function with clipping at TxDSP. M_{dB} is a gain margin to avoid driver nonlinearity by sacrificing RMS. M_{dB} is 1dB in this work. This algorithm thus optimizes digital SNR before the DAC for each β, so that the physical driver gain can be set constant for all β's. Note that a theoretical framework discussed in [1] relies on the constant power constraint (or re-normalization), i.e. physical driver gain changes for each β, while it is not expected to change so "intelligently" for each β in practice.

3. Experimental Results

A four-channel DAC operating at 120 GHz and a coherent driver modulator (CDM) were used to generate dual-polarization (DP) 16-QAM modulated signals at various baud rates with a roll-off factor of 0.1 (Fig. 2a). The driver gain was fixed throughout our experiment. The coherent receiver consists of a high-BW ICR and a 160 Gsa/s analog-to-digital converter. Standard DSP was used to recover the signal, including a 35-tap 2×2 complex-valued MIMO and carrier phase recovery. The S21/link response calibration was performed using 4 FIR filters with 255 taps. The measured frequency-domain magnitudes (Figs. 2b-2d) were fed back to the Tx to synthesize DPE filters, $H_{pre}(f)$. This work studies two cases: back-to-back (B2B), and a link consisting of another six stages of EDFAs and flex wavelength selective switches (WSSs). Fiber is not included in order to eliminate PAPR-induced fiber nonlinearity, but it would not change our conclusion since a greater β (larger PAPR) degrades nonlinear SNR as well [5].

First, we investigate the aforementioned SNR optimizer using an 88.89GBaud DP-16QAM signal as an example. Fig. 2e presents the performance of SNR optimizer for with full-BW DPE (up to 0.55×Baud). Fixed digital gains from 19 dB and 30 dB were applied at Tx-DSP without optimizer. The SNR degradation for β>0.5 suggests that strong DPE should be prohibited to avoid over-clipping and nonlinearity. Our optimizer imposes β-dependent digital gains on DPE waveforms: Generally, a larger PAPR reduces the output RMS substantially. Thus, our SNR optimizer "mimics" the clipping and nonlinearity attributes for all β's. Note that, due to our protective purpose using margin M_{dB}, the blue curves at higher β's gives better SNRs than our optimizer does (red). It does not affect our optimum DPE since their SNRs are low. Now, the question is, can we enhance the SNR for higher β's (in the strong DPE region)?

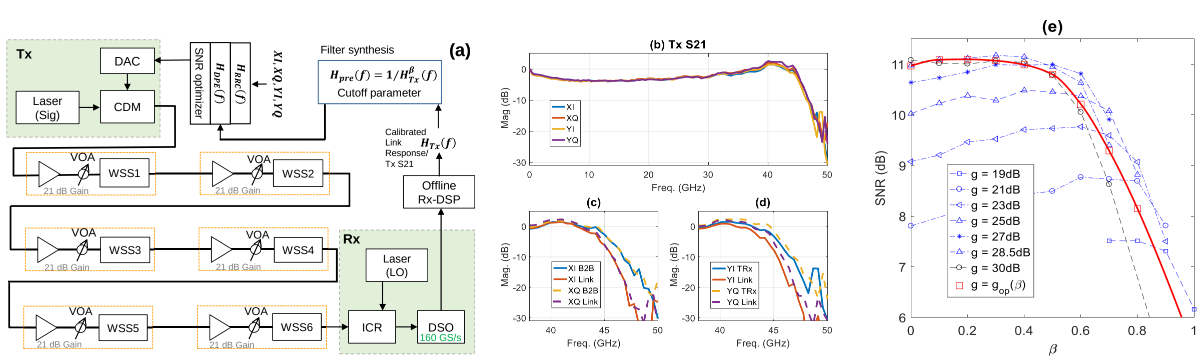

Fig. 2. (a) Experimental setup. (b) Tx S21 (c,d) Comparison between Tx S21 and the entire link including WSSs (e) Performance of the proposed SNR optimizer (red) to guarantee driver's linear operation; Blue, black: fixed gain over all βs.

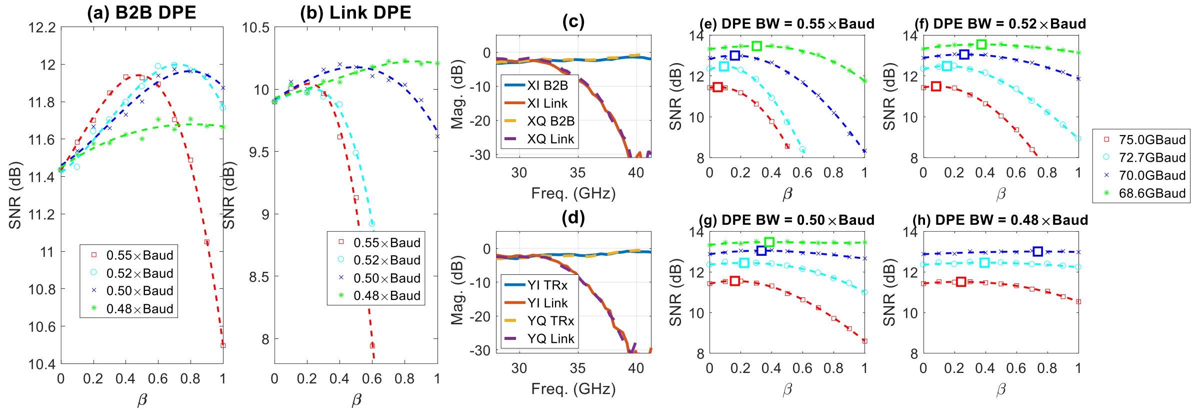

Fig. 3. SNR versus β for different cutoff ratios for DPE (a) for Tx S21 (using 92.31GBaud DP-64QAM) and (b) for the entire link including WSSs. (c,d) Comparison between Tx S21 and the entire link including WSSs, re-calibrated using a 75GBaud DP-16QAM signal. SNR versus β for different Baudrates and cutoff ratios for (e) 0.55×Baud (f) 0.52×Baud (g) 0.50×Baud (h) 0.48×Baud

Fig. 2b shows that the wideband S21's -6dB BW at ~46 GHz while Figs. 2c and 2d show the link (all 100GHz WSSs) frequency response's -6dB BW at ~45 GHz. We applied our proposed low-complexity cutoff approach (i.e., DPE up to a certain cutoff frequency only) in these two channels using a 92.31GBaud DP-64QAM. In Figs. 3a and 3b, SNR drops sharply at $\beta > 0.5$ for full BW DPE (red) since DPE for sharp roll off increases signal's PAPR, and thus RMS decreases and quantization effect kicks in, i.e., a RMS-limited case in Fig. 1b. In B2B (Fig. 3a), for full-BW DPE (red), a local optimum is achieved at $\beta = 0.5$. However, a more "global" optimum can be achieved using a cutoff ratio of 0.52 (cyan) or 0.5 (blue). It is because dropping high-frequency components allows more RMS to enhance SNR, shifting optimal β's toward one. Similarly, for the link (Fig. 3b), the best SNR was found using a cutoff ratio of 0.48 (green) at $\beta = 0.8$. Thus, the cut-off approach enhances RMS in the strong DPE region ($\beta > 0.5$).

The Tx spectral peaking [2] could help relieving the sharp filtering as shown above. Now, let us shift to low baud rate operation (below 40GHz), such that the peaking does not help out anything to relieve WSS filtering. The E2E link responses were measured again by a 75GBaud signal shown in Figs. 3c and 3d. The new link (with WSSs#1, #3 and #5 set to 72, 75 and 78GHz, resp.) reduced the channel bandwidth down to 34GHz, tightly squeezing 68.5G, 70G, 72.7G and 75GBaud signals. Square markers in Figs. 3e-3f indicate the corresponding optimal β's. The 75Gbaud signal experienced the tightest filtering effect among all baud rates, and so the cutoff method can never allow strong DPE. As baudrate decreases, the optimal β's grow larger but still below 0.5. Among all cases, a full DPE is highly prohibited to avoid SNR degradation. However, compared to zero DPE, the achievable SNR gain of each optimal case is around 0.2 dB only. Since the ENoB is between 4 and 5, the optimal β's can never go beyond 0.4 where the reduced RMS and the subsequent quantization effect degrade SNR substantially as shown in Fig. 1c. This proves again that optimal DPE cannot be simply explained or achieved theoretically as mentioned in [6].

4. Conclusion

We show that limited ENoB drives DPE away from strong compensation region (<50% DPE). It is experimentally demonstrated that a low-complexity cutoff approach enhances electrical RMS of a peaking-enhanced wideband Tx without sacrificing the benefits of strong DPE. The results reveal that neither 50 % nor 100 % DPE could achieve the optimum, i.e., one should perform DPE only up to between 0.48×~0.5×fBaud. For very narrow filtering or S21 roll-off, DPE for WSS filtering shows very small SNR gain compared to zero DPE and strong DPE is highly prohibited.

5. References

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