A Novel Analytical Model of the Benefit of Partial Digital Pre-Emphasis in Coherent Optical Transponders

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Abstract A novel analytical model capable of precisely estimating the performance benefit of employing partial digital pre-emphasis in coherent optical transponders is presented. It accounts for component bandwidth limitations, DAC/ADC quantization noise, driver noise, optical link OSNR and DSP equalization. Its accuracy is verified experimentally.

Introduction

The relentless quest for increased optical channel capacity has prompted system designers to move toward more bandwidth-efficient modulation formats[1]–[7], as well as higher symbol rates[8]–[10]. A two-fold line rate increase occurs roughly every 2 years[11], with 90+ GBd systems having now reached commercial maturity[12]. Next generation coherent transponders are expected to operate at well over 100 GBd. At these rates, overcoming severe component bandwidth limitations while reducing receiver equalization noise enhancement requires the application of digital pre-emphasis (DPE) at the transmitter (Tx). DPE, however, does not come for free: it results in increased peak to average power ratio (PAPR) of the signal, which in turn amplifies the effect of quantization noise at the Tx digital-to-analog converter (DAC). This problem is exacerbated as state-of-the-art systems are pushing current electronic and photonic technologies to their bandwidth limits. Fully compensating for the Tx response means reaching high-frequency amplification values of up to ~15-25 dB. In this case, the benefit of minimizing inter-symbol interference (ISI) with DPE can be outweighed by the degradation due to enhanced quantization noise, thus decreasing overall system performance.

It has been demonstrated that applying *partial* DPE can address this contradictory trade-off and maximize overall system performance[13]–[15]. Partial DPE combined with optical pre-emphasis has also been investigated[16], [17]. However, while the reasons for this effect have been identified in the literature, no analytical method to model it has been published yet; system designers resort to empirical brute-force approaches to optimally set up their transponders.

In this work, in addition to analytically modelling the DAC noise, we show that it is possible to accurately predict the amount of partial DPE required for a given link to maximize the SNR; for this, we use digital communications theory of bandlimited channels with linear equalization as described in[18]. The model is experimentally validated using commercial off-the-shelf Tx and Rx components for symbol-rates up to 112.5 GBd. Thanks to its accuracy, the proposed model can be used for efficient calibration and overall SNR maximization of optical transponders employing 2×2 MIMO linear equalization

System model description

Fig. 1(a) shows a general coherent optical system in back-to-back (B2B) configuration, reflecting the experimental setup used in this investigation. The partial DPE is performed

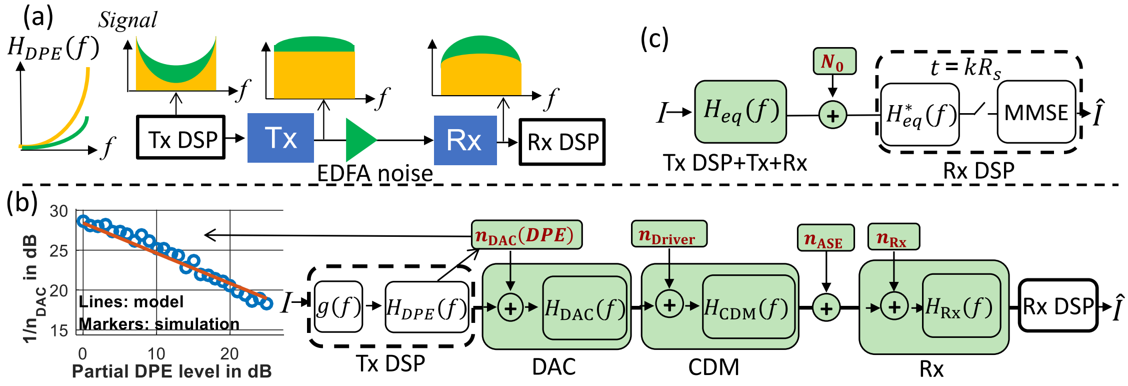

Fig. 1: (a) A general B2B coherent optical system; note that the levels in the spectrum sketches do not represent actual power levels. (b) System model representation, with an example of SNR loss incurred at the DAC under different DPE levels (plot shown on the left). CDM: coherent driver modulator. (c) Equivalent digital system model.

based on the inverse of the transfer function of the transmitter, $H_{Tx}(f)$:

$$H_{DPE}(f) = \alpha / H_{Tx}(f), \quad (1)$$

where α is a scaling factor that adjusts the ratio of partial DPE. The sketched spectra shown in yellow and dark green colors in Fig. 1(a) illustrate the cases of full and partial DPE. Fig. 1(b) shows the proposed system model representation. At the transmitter side, data symbols I are digitally shaped with a given pulse shape $g(f)$ followed by a DPE filter $H_{DPE}(f)$. The DAC is modelled as an additive white Gaussian noise (AWGN) source of variance $n_{\mathrm{DAC}}(DPE)$ accounting for noise amplification as a function of the partial DPE level, followed by a filter $H_{\mathrm{DAC}}(f)$ for the electrical bandwidth limitation. The coherent driver modulator (CDM) is modelled with AWGN of variance n_{Driver}, followed by a filter $H_{\mathrm{CDM}}(f)$. Amplified spontaneous emission (ASE) noise (n_{ASE}) is added in the channel. While fiber impairments such as Kerr nonlinearity and optical in-line filtering can be added in a straightforward manner as described in[18], in this work we focus on the transponder itself, in order to model the benefit of partial DPE. At the receiver side, AWGN of variance n_{Rx} representing all Rx noise sources is added, followed by a filter $H_{Rx}(f)$. Finally, DSP equalization is considered, following the premise that linear 2×2 MIMO equalizers converge to the minimum mean square error (MMSE) solution, for which theoretical analytical expressions exist to compute the SNR[18].

Crucial to the model is the definition of the DAC noise variance, $n_{\mathrm{DAC}}(DPE)$. In our analytical approach, we consider the effective number of bits (ENOB), the level of the applied partial pre-emphasis leading to an increased signal PAPR, and the DAC output power loss due to low-frequency signal suppression. We define the level of partial DPE, $|H_{DPE}(f_{SBW})|^2$, as the pre-emphasis at the baseband signal bandwidth (f_{SBW}), i.e. at 50 GHz for a 100 GBd signal. An example of the dependency of n_{DAC} on the DPE is shown in Fig. 1(b), left. The markers indicate $1/n_{\mathrm{DAC}}$ as calculated at the output of the DAC in numerical simulations where ISI is fully removed, while the solid curve corresponds to our DAC noise model prediction. As can be seen, the trend of the quantization noise increase due to the DPE can be predicted with sufficient accuracy.

The B2B system of Fig. 1(b) can be represented by the equivalent model shown in Fig. 1 (c), which is used for analytical performance estimation. The signal samples are transmitted through an equivalent channel with transfer function $H_{eq}(f)$. This accounts for the concatenation of all component and channel filter transfer functions, and the colored noise power spectral density (PSD). The DSP module consists of a filter matched to $H_{eq}(f)$, a symbol-rate sampler and an MMSE equalizer for which the SNR performance can be analytically computed. The equalizer will find the best compromise between ISI mitigation, and high-frequency noise enhancement at the Rx.

Experimental results

After model validation through numerical Monte-Carlo simulations (not shown here for the sake of brevity), B2B experiments of 100 and 112.5 GBd Dual-Polarization (DP) 16QAM are carried out with the setup shown in Fig. 2. At the transmitter side, the signal is pre-emphasized in the Tx-DSP module. Example DPE responses for 112.5 GBd are illustrated in Fig. 2(a), using different scaling factors α in Eq. (1). Here, the levels of partial DPE are defined as 24.4 dB, 18.4 dB, 9.5 dB, etc., i.e. the values of DPE at 56.25 GHz. The generated waveforms are loaded onto a 120 GSa/s DAC, followed by drivers and a $LiNbO_3$ dual-polarization I/Q modulator. The optical signal is then amplified by an erbium-doped fiber amplifier (EDFA), the input power of which is controlled by a variable optical attenuator (VOA) to vary the link OSNR. The

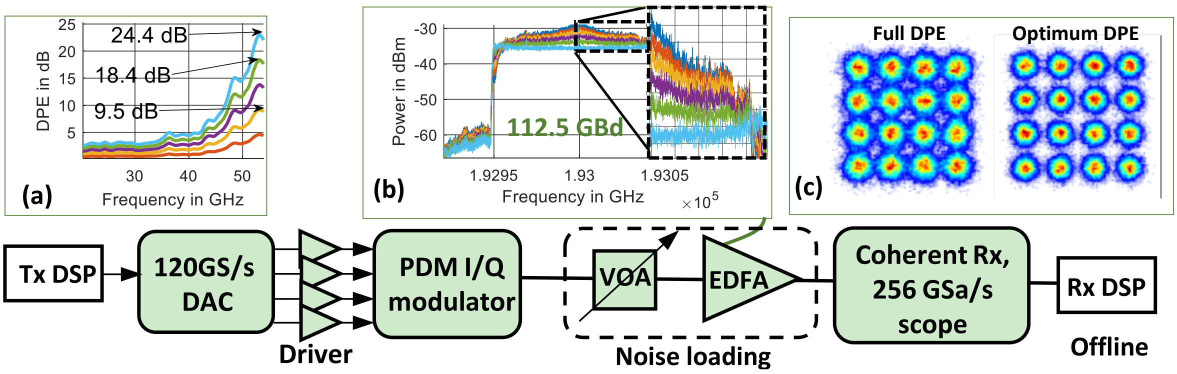

Fig. 2: Experimental set-up. (a) Illustrative DPE responses used in the experiments; the values in dB (e.g. 24.4 dB, 9.5 dB) indicate the DPE levels at the frequency of the baseband signal bandwidth. (b) Signal spectra under different DPE levels. (c) Constellations for the cases of full and optimum DPE levels.

optical spectra measured at the EDFA output for the case of 112.5 GBd are shown in Fig. 2(b), and these correspond to the DPE frequency responses of Fig. 2(a). The signal is detected by a coherent receiver with 70 GHz photodiodes, and a real-time oscilloscope (256 GSa/s, 110 GHz) is used to capture the electrical signal for processing with offline DSP. The performance is estimated in terms of SNR. Two example constellations are shown in Fig. 2(c), for the cases of full and optimum DPE levels.

For the analytical modelling, we use experimentally-obtained frequency transfer functions of all components, and the corresponding Tx noise variances are computed based on the component specifications and our developed DAC noise model. The Rx-side noise variance is chosen to fit the transceiver B2B performance according to the total SNR noise ceiling (i.e. Rx noise and residual Tx noise). The first validation of the model is carried out at 100 GBd for two different OSNR values. The results are shown in Fig. 3(a). It can be seen that the model can accurately predict the SNR at different partial DPE levels. For DPE values higher than 5 dB, the error between model and experiments is smaller than 0.1 dB, i.e. less than 1%. Below 5 dB the error reaches 0.25 dB (~3%). This might be due to the imperfect convergence of the DSP, or an underestimation of the DAC noise in this DPE region. The same applies for the 112.5 GBd case, where the error lies between 1% and 5%, as shown in Fig. 3(b).

Table 1 presents the accuracy of the modelling in terms of the maximum SNR (i.e. at the optimum DPE level), as well as the SNR benefit of the partial DPE, which is defined as the difference between the SNRs at the optimum and full DPE levels. Fig. 3 shows that at 100 GBd a gain of 0.8 dB is obtained, while at 112.5 GBd the gain is increased to 2 dB. As expected, partial DPE is more beneficial when the impact of bandwidth limitation is more severe. Note that the DPE levels in the experiments are varied in steps of 2.4 dB for the 112.5 GBd case and 1.5 dB for the 100 GBd case, whereas in the analytical model the SNR vs. DPE level curves are continuous. This partly accounts for the bigger discrepancy between model and experiment for the 112.5 GBd case, in terms of optimum DPE level (3rd column of Table 1).

Table 1. Accuracy of the model. *Max. SNR*: maximized SNR, *Optim. DPE*: optimum DPE level, both in dB.

Expt. vs. Model	Max. SNR	Optim. DPE	SNR benefit
100 GBd 39 dB SNR	17.8 vs. 17.84	8.2 vs. 8.29	0.8 vs. 0.77
100 GBd 22 dB OSNR	11.0 vs. 11.04	13.3 vs. 13.03	0.1 vs. 0.02
112.5 GBd 35 dB OSNR	15.3 vs. 15.28	14.7 vs. 15.64	2.0 vs. 2.18
112.5 GBd 25 dB OSNR	11.5 vs. 11.52	17.1 vs. 18.57	0.7 vs. 0.67

As observed, SNR at different partial DPE levels can be precisely estimated under given filter responses. Using this model, the optimum DPE amount can be obtained without the need for brute-force optimization.

Conclusion

We have experimentally shown that the benefit of applying partial digital pre-emphasis in coherent optical transponders can be accurately estimated using a DAC SNR degradation model that accounts for signal PAPR variation, together with digital MMSE equalization theory. The proposed model is validated through high-baudrate experiments up to 112.5 GBd. The estimated error is shown to be below 5% for all considered cases.

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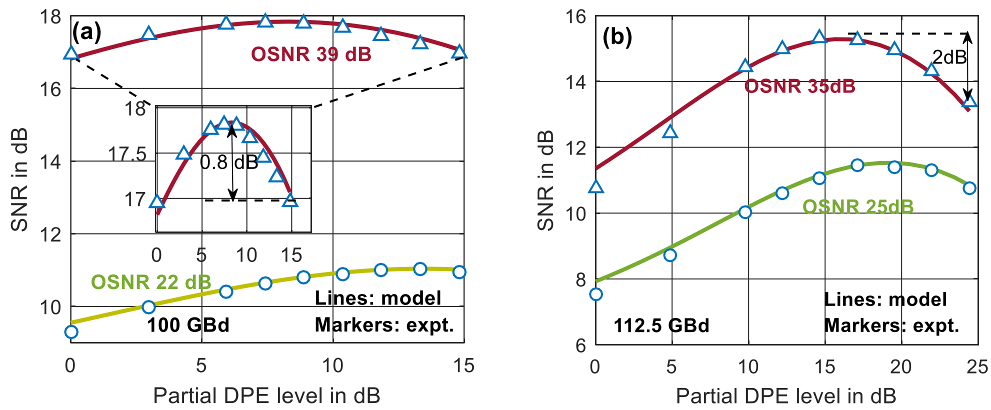

Fig. 3: Experimental results for a DP-16QAM B2B scenario, showing performance as a function of partial DPE at (a) 100 GBd and (b) 112.5 GBd.

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