A General Model for Transceiver Performance Prediction and Pre-emphasis Optimization

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Abstract *We demonstrate that independent transmitter and receiver characterization accounting for colored noise together with a simple semi-analytical model can be used to accurately model transceivers. Measurements show that this model can be used for pre-emphasis optimization in different scenarios, including optical preempahsis and multi-carrier signals.*

Introduction

Driven by lowering the cost per bit, the symbol rate of optical transponders is continuously increasing. The transponder generation operating at about 90 Gbaud [1] is becoming mature. The new generation of transponders capable of operating at 138 Gbaud [2] has already been recently presented. In this scenario, severe device bandwidth limitations are expected and digital pre-emphasis (DPE) becomes necessary to maximize the performance of a transceiver.

The use of DPE and its optimization has already been studied [3-6] and it is well-known that performance optimization requires balancing i) the amount of ASE noise enhancement which is lowest when applying full pre-emphasis and ii) the transmitter noise which is maximized when having full pre-emphasis since the signal tends to have a larger peak-to-average power ratio (PAPR) and more importantly, larger filter losses are obtained since more energy is placed in the part of spectrum that is affected more by transceiver limitations. Beyond DPE, the combination of digital and optical pre-emphasis (OPE) has also been investigated [7,8].

Several models have been previously proposed to predict the optimum DPE [9,10]. The model presented in [9] can accurately predict performance for different pre-emphasis levels. However, it relies on extensive modelling of each of the Tx and Rx devices (DAC, drivers, modulator, photodetectors, TIAs, ADC). Access to each independent transfer function and the amount of noise provided by each device is not always feasible; in a high-bandwidth coherent driver modulator (HB-CDM) and in an integrated coherent receiver (ICR) we only have access to the overall transfer function and noise. The model in [10] has also been proposed to predict the optimal DPE analytically. This analytical model assumes a flat noise at the Tx ignoring its colored nature. Additionally, this model is only valid when the transmitter noise is more predominant than the receiver noise.

In this paper we propose a model based on [10] but in which i) we take into account transmitter and receiver noises independently ii) we take into account that these noise sources are colored iii) MMSE instead of zero-forcing is applied. To do so, we obtain the noises by a series of measurements using deep notch filters applied to the signal at the transmitter DSP to characterize the devices as proposed in [11]. We show that a model based on the Tx and Rx noise floors characterized at a single pre-emphasis level can accurately predict the SNR and optimum pre-emphasis for different pre-emphasis levels and OSNRs. In addition, we show that this model can be applied to both single and multi-carrier signals using the same noise characterization. This model can also predict accurately the performance in presence of inline filtering such as optical pre-emphasis.

System Model

Figure 1 shows a simplified representation of our coherent optical transmission system used for the analysis of transponder impairments on system performance. Signals are shaped at the transmitter DSP by a filter g(f) and digital partial pre-emphasis is applied by a filter $H_{DPE}(f)$ before the transmitter. The signal power after applying DPE is used in the model to take into account the

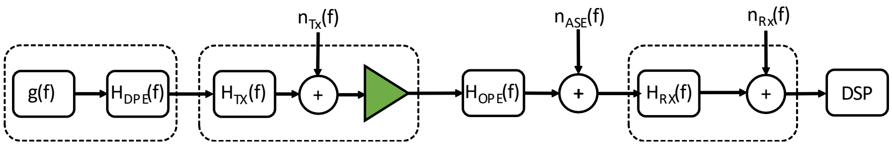

Figure 1 Simplified System Model

PAPR of the generated signal. A filter $H_{Tx}(f)$ accounts for the frequency response of the DACs, driver amplifiers and modulators. A frequency dependent colored noise $n_{Tx}(f)$ is added to account for the linear and nonlinear noise contributions of the different devices in the Tx. This noise is obtained experimentally by selectively adding a symmetric double-sided deep frequency notch into the signal spectrum at the transmitter side DSP to obtain a set of notched signals spanning the bandwidth of interest [11]. The notched signals are measured using a high-resolution optical spectrum analyser (OSA) and stitched together to obtain the colored noise of the transmitter. We assume that device nonlinearities are not significantly impacted by the different amounts of pre-emphasis applied, making it possible to characterize the transmitter once with a select amount of DPE (80% in our case) and apply the measured noise floor to model different transmission scenarios. This requires taking into account the filter loss due to Htx(f) varying between one DPE amount and another. We also assume constellation-shaped signals, in which the notch filtering method can also correctly account for device nonlinearities [12]. A booster EDFA amplifies the transmitted waveform to a fixed power level at the end of the transmitter. OPE can be applied inline to shape the signal which has been shown to improve system performance when used jointly with DPE compared to using only DPE. Flat ASE noise $n_{ASE}(f)$ is added to model the link OSNR.

The receiver is similarly modelled by a colored noise floor $n_{Rx}(f)$ consisting of all the linear and nonlinear Rx noise contributions and a filter $H_{Rx}(f)$ to model the frequency response of the photodetectors and coherent Rx. The colored noise is similarly obtained from the set of notched signals after ADC digitizing and FFT without any further DSP processing. This colored noise contains both transmitter and receiver contributions labelled as $n_{TRx}(f)$. The receiver-only noise floor $n_{Rx}(f)$ can be readily obtained as $n_{Rx}(f) = n_{TRx}(f) - n_{Tx}(f)$. The transmitted signal and the noises $n_{Tx}(f)$, $n_{Rx}(f)$ and $n_{ASE}(f)$ are used as inputs to an MMSE equalizer with all intermediate channel filtering to obtain an SNR estimate for a given transmission scenario.

Our model also takes into account effective SNR measurements, at the same DPE level as the noise characterization, to account for the penalty between ideal SNR and effective SNR after DSP caused by DSP penalties for example [9].

Experimental Results

The setup shown in Fig. 2(a) is used to characterize the transceiver as well as validate the model. Partial DPE is applied to the signals at the Tx DSP. The waveforms are synthesised by a 120GSa/s DAC followed by RF driver amplifiers and a LiNbO3 dual-polarization I/Q modulator (DP-IQM). Both the characterization and measurements are performed with a 105 Gbaud, CS64QAM with 5 bits/symbol entropy signal. As mentioned, for the characterization step, a series of double-sided notch filters are applied at the Tx DSP to generate a set of notched signals spanning the signal bandwidth. The modulator is followed by a booster EDFA to amplify the signal power to a suitable level. A 3-dB coupler is placed after the EDFA such that one branch goes to the high resolution OSA used to characterize the noise floor of the transmitter. This is to ensure that the noise level in the notch is well above the noise floor of the OSA. The second branch enters a wavelength selective switch (WSS) which is used to limit the out of band ASE noise from the EDFA and to selectively provide OPE when required. The signal from the output of the WSS is amplified by a second EDFA preceded by a series of variable optical attenuators (VOAs) to control the input power in order to vary the link OSNR. An OSA after the second EDFA is used to estimate the OSNR. The EDFA output goes through a second WSS to remove out of band noise, and a final EDFA and VOA to provide adequate power into a coherent receiver. The coherent receiver consists of 70 GHz photodiodes and a 256 GSa/s oscilloscope before receiver-side DSP processing. As will be shown, we have also performed a set of measurements in which the scope is operated at

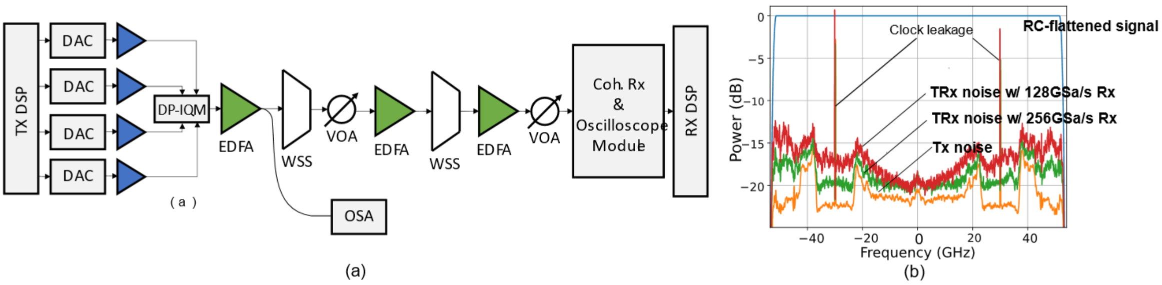

Figure 2 (a) Experimental Setup (b) raised-cosine flattened signal and noises

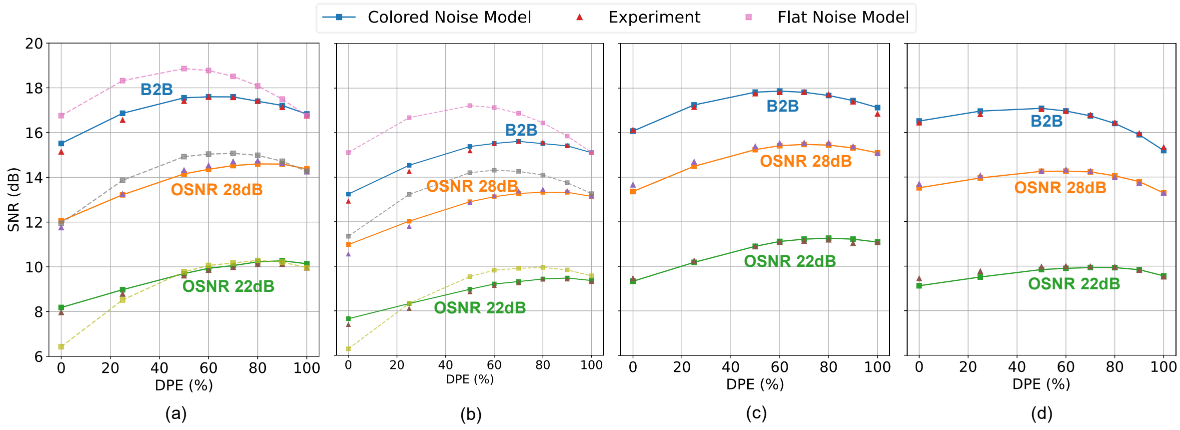

Figure 3 Model prediction of SNR vs DPE at 105 Gbaud (a) 256GSa/s ADC (b) 128GSa/s ADC (c) 256GSa/s ADC with 30% OPE (d) SCM with 8 subcarriers (global SNR is used as a metric [13])

128 GSa/s in order to highlight the accuracy of this model in the presence of a different noise balance between transmitter and receiver, where the receiver noise is more significant. For receiver characterization the notched signals are captured with the oscilloscope to measure a noise floor consisting of the combined Tx and Rx noise contributions. The noise floors measured by the spectrum analyser and the oscilloscope are shown in Fig. 3(b) for both ADC sampling rates after normalization and signal flattening with respect to a raised-cosine (RC) at 105Gbaud.

In Fig. 3(a), we present the SNR prediction of our model and the measurements for different DPE level and OSNR including a point at the maximum achievable OSNR referred as B2B. Additionally, we also compare our model to a model based on [10] where only flat noise is added at the transmitter side based on the SNR measured at 100% DPE. Our model correctly predicts an optimal DPE of 60% for back-to-back (B2B) with a maximum error of 0.1dB for pre-emphasis values larger than 50% For lower pre-emphasis, our model tends to overestimate the SNR which could be due to larger nonlinearities. However, it has been shown analytically that the optimum DPE is always larger than 50% for single-carrier signals. In comparison, the flat noise model predicts an optimal DPE of 50% with an SNR error of 1.25dB. At 22dB OSNR our model again correctly predicts an optimum DPE of 90% with 0.1dB error at most for >50% DPE. The results when operating the ADC at 128 GSa/s are shown in Fig. 3(b). In this case, the optimal DPE is 70% in B2B due to the increased receiver noise contribution which is accurately predicted by our model with a maximum SNR error of 0.2dB (>50%DPE). The flat noise model consistently predicts 50% as the optimum DPE with an error of 1.9dB. At 22dB OSNR the optimal remains at 90% with a maximum error of 0.15dB.

It is important to highlight the importance of colored noise as well as the separation of Tx and Rx. In cases where transceiver noise is dominant (high OSNR) it can result in the optimal DPE shifting away from 50% to 60-70%. However, at low OSNR scenarios where ASE is the dominant source of noise, both models converge to the same conclusions apart from the difference between MMSE (used in our proposed model) and ZF (as suggested in []10]) for low pre-emphasis.

Figure 3(c) shows the effect of using joint digital and optical pre-emphasis. The taps of the first WSS are adjusted to provide OPE amounting to 30% and the DPE percentages are adjusted accordingly. It can be seen that the maximum SNR is 0.2dB higher than the case of Fig. 3(a). The model correctly estimates the new SNR with a maximum error of 0.5dB. Finally, Fig. 3d demonstrates the versatility of this model by applying the noise floors characterized with a single carrier signal to predict the system performance with an 8-subcarrier multiplexed (SCM) signal. In B2B the optimal DPE is 50% which is correctly predicted by the model with a maximum error of 0.15dB. We should emphasize that this good prediction for SCM is only possible by using a model accounting for colored noise.

Conclusions

In this paper we presented a low complexity semi-analytical model based on transceiver noise floor characterization. Our proposed model benefits from taking into account the colored noise of the transmitter and receiver independently, and therefore it can be applied over many different scenarios including different noise balance from transmitter and receiver. We have also shown the flexibility of this model by applying it over system with optical pre-emphasis and multi-carrier signals.

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