Proposal of LUT-based transmitter nonlinearity compensator with precursor compensation for Short-Reach IM/DD PAM Signalling with Tomlinson-Harashima Precoding (THP)

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Abstract *We propose a novel Look-Up-Table-based transmitter non-linearity compensator for Tomlinson-Harashima Precoding (THP) based PAM signalling with the capability of both pre-cursor and post-cursor compensation, and experimentally show its effectiveness to improve BER performance better than Rx-side Volttera-series equalizer in 40-GBaud PAM4 signalling.*

Introduction

Due to the rapid and steady growth of inter and intra-data centre traffic, the next-generation simple and cost-effective short-reach IM/DD optical transceivers with several times higher transmission capacity is soon in serious needs, and its supporting signalling techniques are eagerly studied. For example, PAM4 signals are introduced to realize 50- and 100-Gbit/s/Lamda IM/DD signalling (Ex. [1][2][3]) in IEEE 400GbE standard, however, PAM signals have intrinsic performance issues compared with binary signals, such as theoretically less power budget by 4.8 dB, higher susceptibility to inter-symbol-interference due to bandwidth limitation, AD/DA dynamic range, and so on. Thus, improvement of PAM transceiver power budget is seriously required; one of the major power loss are their limited extinction ratio (ER) around 3 to 4 dB. However increase of ER tend to induce severe transmitter NL degradation from RF amplifier or optical modulator NL response. Another solution is the application of various advanced DSP techniques such as DFE, MLSE, and THP [4][5], and so on. Among them, THP has the advantages of less computational power and the absence of noise enhancement and error propagation, and its use for various fibre transmission[6][7][8][9][10] have been reported.

However, the simultaneous compensation of transmitter linear and NL impairments is a challenging issue for THP: THP equalizes causal linear channel impairment h(t) by its inverse function $h^{-1}(t)$ at the transmitter side, however its use of modulo function (MOD) makes the NL compensation difficult. The receiver-side Volterra-series NL equalizer [11] is known to be very effective to cancel out such NL distortion, but it requires very high computational power and is not yet practical to be implemented in commercial IM/DD receiver. Also in terms of interoperability with the other vendors' receivers, it seems to be desirable to alleviate Tx-side NL degradation in the transmitter itself. For example, in order to separately qualify transmitter performance for the measure of interoperability, the concept of TDECQ (Transmitter and dispersion eye closure, or TECQ) is introduced in IEEE 802.3 which assumes an ideal receiver only with short (4-tap) linear FFE.

For the simultaneous Tx-side compensation of linear and NL impairments in THP, the analytical compensation of causal LPF and memory-less NL [12] and LUT-based NL-compensation scheme [13] have been reported: However, both schemes are limited to post-cursor NL compensation due to the nature of THP, thus require additional Rx-side NL compensator (NLC) to reduce the effect of pre-cursors.

In this paper, we propose a novel LUT-based Tx-side NLC with pre-cursor compensation for high-speed THP-PAM signalling without the need for computationally-heavy Rx-side Volterra-series NLC, and experimentally show its effectiveness in BER floor and power budget improvement with 40-km SSMF transmission.

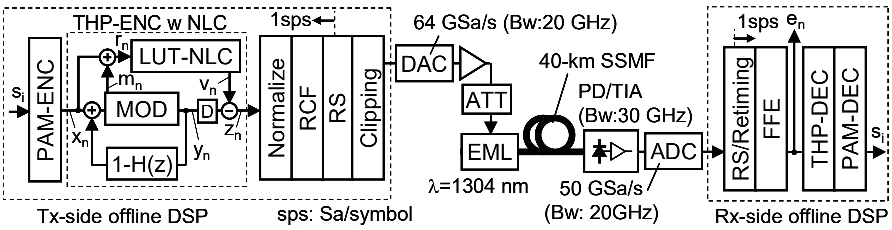


Fig. 1: Experimental 40-GBaud THP-PAM4 transceiver set up with the proposed LUT-based NLC (LUT-NLC). ENC/DEC: encoder/decoder, MOD: modulo operation, RCF: raised-cosine filter, RS: re-sampling, CLP: clipping, ATT: Attenuator, EML: electro-absorption modulator integrated laser, FFE: Linear feed-forward equalizer.

LUT-NLC with precursor compensation

Typical transceiver non-linearities, such as signal satuation or clipping, seems to be memory less, however when it interacts with the linear channel response, time-domain NL compensation is required. Some channel filters, such as Nyquist and Bessel filters, are non-causal filters with non-negligible pre-cursor responses, thus NL compensation is required to have pre-cursor compensation capability. To realize it, we introduce a novel THP encoder (THP-ENC) with LUT-based non-linear compensater (LUT-NLC) as in Fig.1. Eq. 1 represents the operation of typical THP encoder,

$$y_n = \mathrm{mod}_{2N}\left(x_n + \left(1 - H(z)\right) \otimes y_n\right) \quad (1)$$

where x_n is the input PAM-N sequence with the symbol spacing of 2, y_n is the output sequence from the THP encoder, and H(z) is the channel response, mainly corresponds to the transmitter bandwidth limitation in this paper. The index sequence r_n of the LUT-NLC is the extended signal set of the THP signal, which is the sum of the input PAM-N sequence x_n and the result m_n of rounding operation of modulo circuit as,

$$r_n = x_n + m_n \quad (2)$$

where m_n=-2N when modulo circuit performs rounding down operation, m_n=2N when rounding up, and otherwise m_n=0. The Eq. 3 represents the indexing of the LUT-NLC,

$$v_n = f\left(\mathrm{r}_{\mathrm{n-q}}, \mathrm{r}_{\mathrm{n-q+1}}, \ldots \mathrm{r}_{\mathrm{n}}, \ldots \mathrm{r}_{\mathrm{n+p}}\right) \quad (3)$$

$$z_n = y_n - v_n \quad (4)$$

where q and p are the number of pre-cursor and post-cursor symbols used for LUT indexing, and v_n is the Tx nonlinear distortion for the each input sequence stored in the LUT. The configuration of LUT is described as (q,p) through the paper, and all the LUT entries are experimentally pre-calculated from the known transmitted sequences by averaging the residual non-linear symbol errors e_n obtained from a referenced receiver with a linear adaptive filter before a THP-decoder. It should be noted that the proposed NLC is intended to compensate only the Tx impairments and the value of LUT entries are pre-fixed to improve interoperability with various receivers, and no feedback from the receiver in use is considered in this paper.

The compensated signal z_n is obtained by subtracting v_n from the THP output signal y_n as in Eq. (4). When using pre-cursor compensation, proper delay D should be inserted to match the timing of v_n and y_n. The average power of the transmitted sequence should be normalized to the original one to suppress the over compesation of non-linearity.

The advantages of the proposed NLC are; 1) the LUT-NLC is indexed by the extended symbol sequences of THP, which correctly reflects the modulo opeartion of the THP encoder, and 2) It enables the use of precursors for NL compensation. Both results in precise NL compensation and less transmitter penalties.

The number of entries of the LUT-NLC is M^{p+q+1}, where M is the symbol number of extendend PAM signal, typically 6 or 8 for THP-PAM4. In our experiments, we evaluated two cases of channel memory m of 3 or 5, where m=p+q+1, which corresponds to the LUT entries of 6^3=216 to 6^5=7776. It should be noted that 80-% of experimental LUT entries are zero or negligibly small because the compensation is required only for symbol sequences corresponding to very high (or low) peak amplitude and also some signal transitions are prohibited in THP.

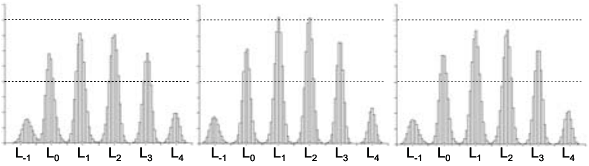
Experimental Setup

Fig. 1 shows an experimental 40-GBaud THP-PAM-4 transceiver setup: In the Tx-side offline DSP, a PAM sequence is passed to the NL-THP encoder with a pre-calculated LUT-NLC. We used a random PAM sequence with the length of 120000 symbols for the pre-calculation of LUT entries, and an independent PAM sequence of 40000 symbols is used for BER evaluation. The experimental Tx response H(z) is approximated by 3-tap LPF to whiten noise distribution, which corresponds to M=6. The amplitude of the output signal is normalized and Nyquist filtering by a raised cosine filter (Roll off factor Ro=0.05), resampling and clipping are performed. Then, it is fed to a 64-GSa/s 8-bit DA converter (3-dB bandwidth: 20 GHz) and its output signal drives a 1.3-μm electro-absorption modulator integrated laser (Bw: 28 GHz) through a driver amplifier and an RF attenuator. The receiver has a pin-PD/TIA front end (3-dB bandwidth: 30 GHz) followed by an 8-bit AD converter with the sampling rate of 50 GSa/s (Bandwidth: 20 GHz). In a Rx-side offline DSP, re-sampling and timing-recovery is performed to the digitized received signal, and adaptive symbol-spaced linear FFE with 51 taps, a modulo THP decoder, and a PAM decoder for bit error ratio (BER) calculation are applied.

Experimental Results

Fig. 2 shows the experimentally received 40-GBaud THP-PAM signal histograms: Without NLC, the histogram in (a) shows strong distortion around L_0 and L_{-1} by hitting zero levels due to high optical modulation ratio of 88.4 %.

The use of the LUT-NLC in (b) and (c) improves the orientation of the histograms very much, and it is shown that the one with 2-tap pre-cursor and 2-tap post-cursor compensation (b) shows the tightest distribution, thus ,highest peak levels.



(a) w/o NLC (b) w NLC(-2,2) (c) w NLC(4,0)

Fig. 2: Experimentally received histograms of 40-GBaud THP-PAM4 signal with or without proposed LUT-NLC at 88.4-% optical modulation ratio with linear FFE. L_0-L_3 are the original PAM-4 symbols, and L_{-1} and L_4 are the THP extended symbols: (a) without LUT-NLC, (b) with NLC (-2,2) (pre- and post-cursor compensation) and (c) with NLC (4,0) (only post-cursor compensation).

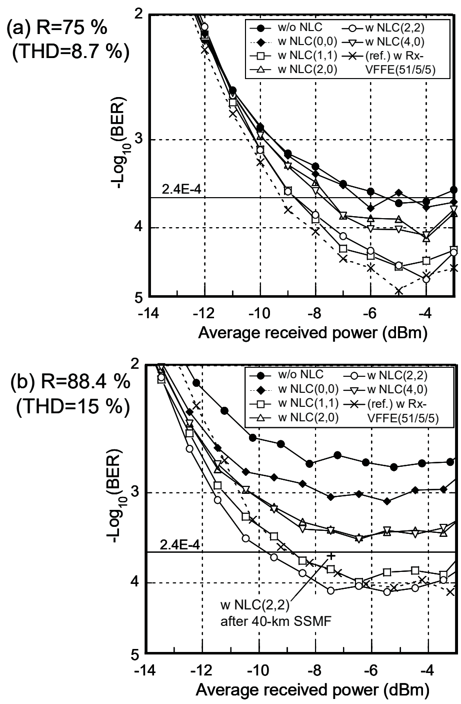


Fig. 3: BER performances of experimentally received 40-GBaud THP-PAM signals with or without proposed LUT-NLC for optical modulation ratio R=73 % and 88.4 %. Cross symbols corresponds to 40-km standard SMF transmission.

Next, back-to-back BER performances of experimentally received 40-GBaud THP-PAM signals are evaluated at two optical modulation ratio R of (a) 75 % and (b) 88.4 % by changing the EML driving amplitude with and without 3-dB RF attenuator (ATT). Total harmonic distortions of the two conditions are measured using 4-GHz sinusoidal wave to be 8.7 and 15.0%, respectively. In Fig.3(a), the transmission link shows less NL, and the BER curve without NLC shows the floor around KP4-FEC limit (2.4E-4).

The NLCs with only post-cursor compensation (triangles) improve the BER floor to about 1E-4, and further improvement to 3E-5 are obtained by the proposed LUT-NLC using both pre and post cursors (open circles and squares).

By increasing the optical modulation ratio to 88.4 % Fig. 3(b), it is shown that the BER floor without NLC (closed circles) is degraded to 2E-3 due to higher NL driving condition of optical modulator. It is also shown that the use of the proposed LUT-NLC improves the BER floor by 1/20 to less than the KP4-FEC limit, where the use of LUT-NLCs with only post-cursor compensation (2,0) and (4,0) (open triangles) improves the BER floor only to 4E-4. The dashed line with diagonal crosses shows the reference BER curve with Rx-side Volterra-series NLC using the second-order and third-order Kernels, both with the memory length of 5 symbols. It is shown that the proposed LUT-NLC(2,2) shows the best sensitivity of -9.7 dBm surpassing the one with Rx-side Volterra NLC by 0.7 dB, since Tx-side NLC effectively improves Tx-SNR. The total transceiver power budget is improved to 15.4 dB and we successfully conduct a 40-km SSMF transmission (span loss: 13.2 dB) with NLC(2,2) as a cross symbol in Fig.3(b).

Conclusions

We propose a novel LUT-based compensator of Transmitter non-linearity for high-speed IM/DD THP-PAM signaling with pre-cursor compensation capability and show its effectiveness to improve transceiver power budget with the better performance than the Rx-side Volterra-series NLC.

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