Improvement of Tomlinson-Harashima Precoding Performance for Bandwidth-Limited IM/DD Systems

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Abstract *We propose to apply an additional filter between Tomlinson-Harashima precoding (THP) and inverse channel predistortion to match the received signal spectrum with the THP target spectrum. 92 GBd PAM4 back-to-back and 1 km SSMF experiments show an improved performance by the additional filter.*

Introduction

The data traffic inside datacenters is continuously growing. For the optical links, that are deployed in this short reach application, cost efficient intensity-modulation/direct-detection (IM/DD) systems with pulse amplitude modulation (PAM) are currently preferred over coherent systems. However, increasing data rates lead to more severe impairments due to bandwidth-limited transceiver components. These impairments need to be addressed by efficient digital signal processing (DSP) at the transmitter and receiver, to enable a successful transmission. As a transmitter-side counter part of decision feedback equalization (DFE), Tomlinson-Harashima precoding (THP) can achieve improved performance in transmission systems, that are impaired by bandwidth limitations and chromatic dispersion induced power fading[1]–[4]. In this paper, we propose to apply a simple finite impulse response (FIR) filter between THP and inverse channel predistortion to match the received signal spectrum with the equalizer target spectrum. By doing this, we show performance improvement compared to the conventional THP in 92 GBd PAM4 back-to-back and 1 km SSMF measurements in C-band. The performance gain by the additional FIR filter is larger for smaller numbers of coefficients in the linear receiver feed forward equalizer (FFE).

Proposed approach

The THP output signal for PAM-M is approximately uniformly distributed over the amplitude range $[-M, M)$ and has a flat spectrum over the signal frequency range. To overcome the attenuation of the high-frequency signal parts due to the bandwidth-limited transceiver components, a predistortion with a transfer function, that corresponds to the inverse characteristic of the channel, is typically applied. This combination aims at a flat spectrum of the received signal. The receiver equalizer targets at the effective data sequence (EDS), that, however, depending on the THP coefficients, does not have a flat spectrum. Therefore, a mismatch between the predistorted THP output signal and the equalizer target exists. This mismatch can be removed by an FIR filter that uses the same coefficients as the THP. Fig. 1 shows this approach for the simple case of 1-tap THP. As shown on the right part of Fig. 1, THP and the FIR filter can be combined to save a multiplier. The extension to multiple THP coefficients is straightforward. The output signal $v(k)$ after the precoder now corresponds to the EDS and therefore to the equalizer target signal. This simple extension can be beneficial for systems, in which bandwidth limitations of the transceiver components restrict the performance of the transmission system.

Experimental investigations

The transmission system setup together with the DSP steps is shown in Fig. 2. Random data is generated and mapped on PAM symbols, before precoding and application of the additional FIR filter. Afterwards, the inverse channel predistortion is performed. We used 30 coefficients for predistortion and the coefficient values were calculated by applying the Burg

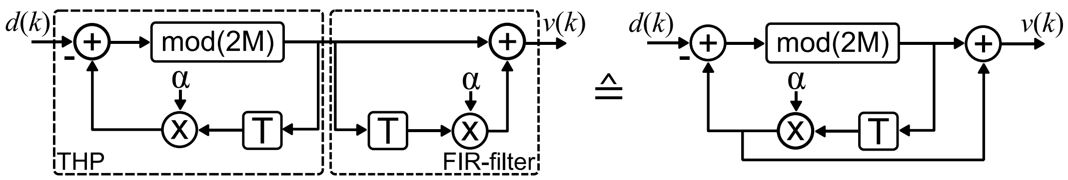

Fig. 1: Block diagram of 1-tap THP with FIR filter and combined structure. $d(k)$ is the PAM4 input sequence and $v(k)$ the THP effective data sequence.

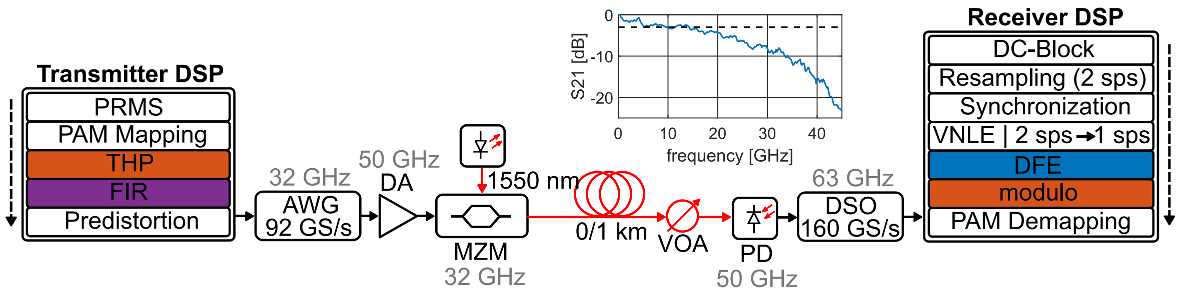

Fig. 2: Transmission system setup and DSP. The inset shows the spectrum of the optical back-to-back configuration. PRMS: pseudo-random multilevel sequence, THP: Tomlinson-Harashima precoding, FIR: finite impulse response, AWG: arbitrary waveform generator, DA: driver amplifier, MZM: Mach-Zehnder modulator, VOA: variable optical attenuator, PD: photodiode, DSO: digital storage oscilloscope, VNLE: Volterra nonlinear equalization, DFE: decision feedback equalizer.

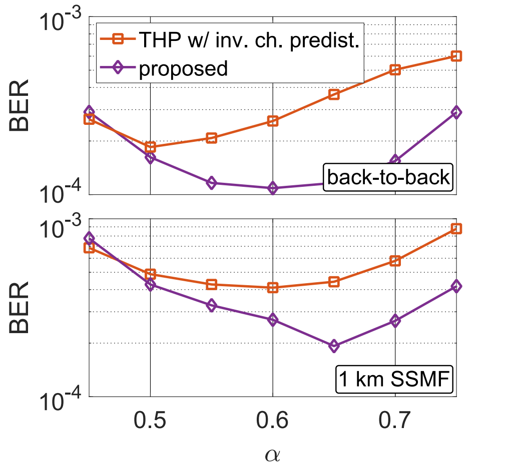

Fig. 3: Comparison of the performance of conventional THP and the proposed approach for different values of the THP coefficient α in 92 GBd PAM4 back-to-back and 1 km transmission.

algorithm[5] on the received signal after back-to-back transmission. The transfer function of the predistortion was clipped in frequency domain at the value leading to the lowest BER for the respective DSP configuration. The resulting signal is fed into an arbitrary waveform generator (AWG) with a 3 dB bandwidth (BW) of 32 GHz and a sampling rate of 92 GS/s. The analog output signal is amplified by a 50 GHz driver amplifier and modulated on a 1550 nm optical carrier by a 32 GHz Mach-Zehnder modulator. After transmission over the fiber, the input power into the photodiode, which has a BW of 50 GHz, is controlled by a variable optical attenuator. The electrical output is digitized at 160 GS/s by a 63 GHz digital storage oscilloscope. In the receiver DSP, the DC-part of the signal is blocked and resampled to two samples per symbol. The sampling phase is synchronized to symbol timing, and Volterra nonlinear equalization (VNLE) is applied to overcome linear and nonlinear impairments of the channel. Kernels up to the third order are used and the VNLE with the memory lengths of M_1, M_2, M_3 for the first, second and third order, respectively, is denoted

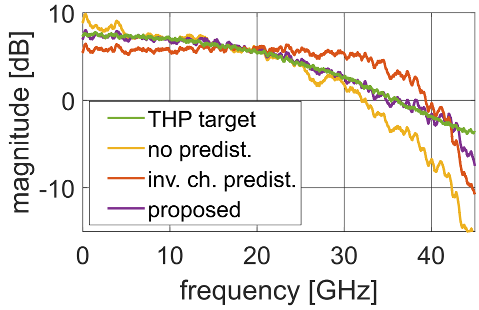

Fig. 4: Comparison of the received THP signal spectra for back-to-back transmission with α = 0.5 and the receiver equalizer target spectrum.

by VNLE(M_1, M_2, M_3). For comparison with THP, DFE can be applied after VNLE. When THP is applied, a modulo operation is used before the PAM4 symbols are de-mapped and the bit error rate (BER) is calculated. The inset of Fig. 2 shows the spectrum of the optical back-to-back signal. The 3 dB bandwidth is approximately 14 GHz.

In Fig. 3, the performance of THP and the proposed scheme in 92 GBd PAM4 measurements at a received optical power (ROP) of 6 dBm, are compared for different values of the THP coefficient α. A VNLE(200,11,11) is used at the receiver for this comparison. As visible, the proposed scheme, which applies the additional FIR filter after THP, reaches lower BER values for both back-to-back and 1 km transmission. The optimal values for the THP coefficient are α = 0.6 for the back-to-back case and α = 0.65 for the 1 km transmission for the proposed approach and α = 0.5 and α = 0.6 for standard THP, respectively. The reason for this gain is illustrated in Fig. 4, which shows the spectra of the THP target signal, and the received signals after applying THP without any predistortion, THP with inverse channel predistortion, and the proposed approach after back-to-back transmission for a THP coefficient of α = 0.5. The signal without any predistortion is strongly attenuated at high frequencies above 30 GHz and, therefore, does not match the target spectrum. The received

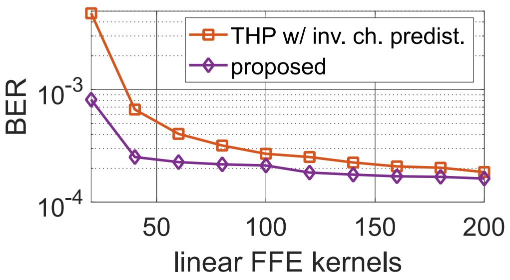

Fig. 5: Impact of the number of linear receiver equalizer kernels on the performance of conventional THP and the proposed scheme.

signal after conventional THP with the inverse channel predistortion has a flat spectrum for frequencies up to 30 GHz and does not fit to the target spectrum either. The received spectrum after the proposed approach, however, is very similar to the target spectrum. Although the spectra are better matched, no significant gain of the proposed scheme is observable for back-to-back transmission and α = 0.5 in Fig. 3. The reason is the high number of receiver equalizer coefficients, which allows a compensation of the mismatch. In Fig. 5 the impact of the number of linear receiver equalizer kernels on the BER is shown for the same conditions. The proposed scheme exhibits a significant gain for low kernel numbers and achieves nearly optimal performance already with 40 linear kernels. The conventional THP with inverse channel predistortion needs more than 100 kernels to reach a similar performance. Therefore, the better match achieved by the proposed scheme allows a reduction of the receiver equalizer complexity.

Fig. 6 shows the BER as a function of the received optical power (ROP) for back-to-back and 1 km measurements with selected DSP configurations. Additionally to the conventional THP and the proposed scheme, the performance of only VNLE and VNLE combined with 1-tap DFE without any precoding is given as a reference. Results for a VNLE(40,11,11) as well as for a VNLE(200,11,11) are provided.

For back-to-back transmission, a clear advantage of the proposed scheme over the other approaches is visible for a receiver equalizer with 40 linear kernels. The conventional THP is outperformed by DFE for high ROP values. The VNLE(200,11,11) improves the performance of all schemes, but the impact is least significant for the proposed approach. When 200 linear kernels are used, the proposed scheme shows a similar performance as the receiver with a 1-tap DFE. For ROP values above 4 dBm, the proposed approach performs better than conventional THP.

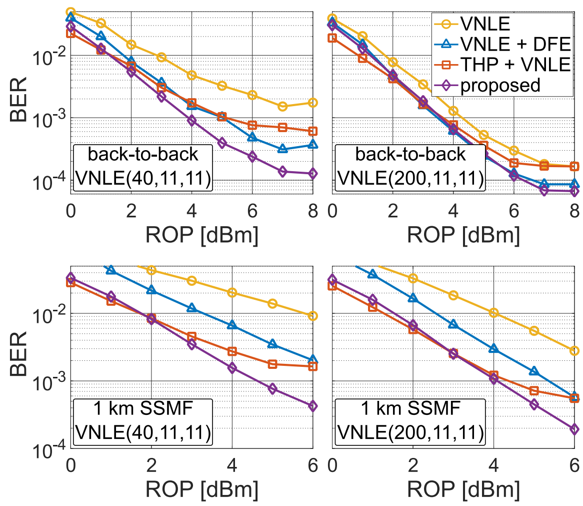

Fig. 6: Results for the bit error rate over received optical power for 92 GBd PAM4 back-to-back and 1 km transmission. The proposed approach is compared to different standard DSP schemes for 40 and 200 linear receiver equalizer kernels.

For 1 km transmission, both the conventional THP and the proposed approach outperform the schemes that do not apply precoding. Again, the performance gain of the proposed scheme is more significant when the receiver equalizer uses only 40 linear coefficients. For the long equalizer with 200 kernels, no gain can be achieved for ROP values up to 4 dBm, but the error floor is improved for higher ROPs.

Conclusions

We showed, that it can be advantageous to use an additional filter after Tomlinson-Harashima precoding in a bandwidth-limited IM/DD system.

We proposed a simple filter that can be implemented without additional multipliers and, therefore, without significant increase of complexity at the transmitter.

The filter, whose output corresponds to the target sequence of the receiver equalizer, makes the received sequence spectrum match the target spectrum.

Experimental results for 92 GBd PAM4 in back-to-back configuration and after transmission over 1 km fiber in C-band show a gain over conventional THP, especially when the receiver equalizer uses a lower numbers of linear kernels.

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