# Comparison of PAM Formats for 200 Gb/s Short Reach Transmission Systems

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**Abstract:** We compared the performance of PAM4, PAM6 and PAM8 experimentally at 224/225 Gb/s using different DSP schemes including Tomlinson-Harashima precoding (THP). PAM6 shows the best overall performance. For PAM4 THP shows a large gain.
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## 1. Introduction

The traffic inside data centers is growing continuously. To satisfy the demand for higher data rates, systems with a high rate per wavelength are necessary. A cost-efficient solution for 800 GbE could be a 4-wavelength IM/DD system with a net rate of 200 Gb/s/λ. To reach that rate, either high symbol rates or high-order modulation formats need to be applied. Besides PAM4 and PAM8, also PAM6 as an intermediate format in terms of bits per symbol is a good candidate. Different publications show the applicability of PAM6 for high-bitrate short-reach systems [1,2].

The digital signal processing (DSP) schemes play an important role in the realization of such systems. An effective way to overcome the impairments like strong inter-symbol interference (ISI) is the combination of feed-forward equalization (FFE) and maximum-likelihood sequence estimation (MLSE). Alternatively, decision-feedback equalization (DFE) can be applied together with FFE to improve the performance. To avoid the error propagation in DFE, Tomlinson-Harashima precoding (THP) at the transmitter side has been successfully applied for high data rate short-reach systems [3,4].

Up to now, a fair comparison of THP with the alternative scheme of receiver side FFE + MLSE has not been shown for a 200 Gb/s/λ system. Also, the performance of THP for PAM6 has hardly been analyzed before. Both topics are investigated experimentally in this paper for a fixed gross data rate of 224/225 Gb/s, resulting in a net rate of 200 Gb/s, over up to 1 km SSMF in C-band.

## 2. Modulation formats and precoding

The mappings for the standard formats PAM4 and PAM8 can be done symbol-wise and Gray coding can be applied. For the mapping of bits on PAM6 symbols, the time is utilized as an additional dimension. To keep the implementation simple, 5 bits can be mapped on 2 consecutive symbols, therefore only 32 of the 36 two dimensional symbols are used. These symbols create a 2-dimensional plane, which enables the use of a mapping optimized for the 32-QAM constellation, as shown for example in [1]. The decoding needs to be done jointly for the symbol pairs.

THP can be applied for the different PAM mappings with minor adaptations. The structure is shown in Fig. 1 a, where $d(k)$ is a PAM input symbol, $f_{\pm M}$ a specific modulo operation, $H(z)$ the THP transfer function and $x(k)$ the output symbol. A linearized form of the THP structure in shown in Fig. 1 b, where $p(k) \in \mathbb{Z} \cdot 2M$ describes the impact of the modulo operation, and $v(k)$ defines the so called effective data sequence (EDS), which is the sequence the receiver-side equalizer aims at, if THP is applied. For the application to different PAM formats, only the modulo operation needs to be adapted. The THP transfer function needs to be estimated for each specific transmission system. This cannot be done at the transmitter, since no channel information is available. Therefore, the transfer function is optimized at the receiver using an FFE + DFE structure that estimates the channel using a training-based and decision-directed LMS algorithm. Only the DFE transfer function is handed over to the transmitter and is applied for THP without any further adaptations. Applying this transfer function at the transmitter rather than at the receiver can be advantageous, because the necessary symbol decisions in DFE and the resulting error propagation can be avoided.

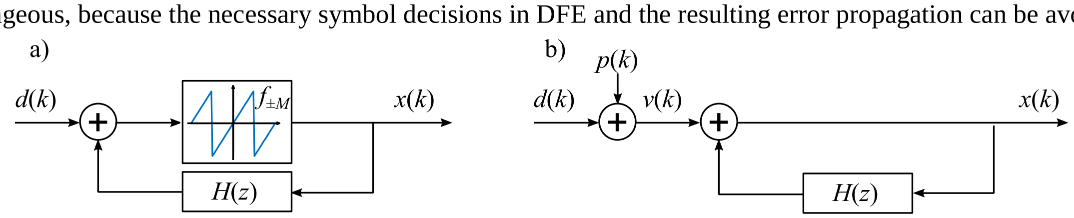


Fig. 1: a) actual structure and b) linearized structure of the Tomlinson-Harashima pre-coder.

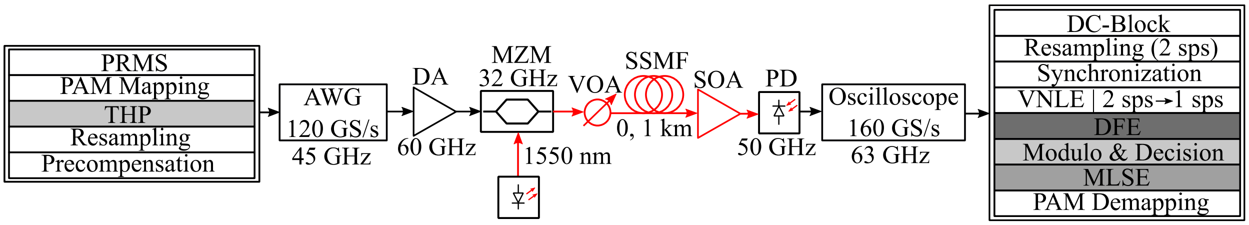


Fig. 2: Setup of the transmission system and DSP structure. AWG: Arbitrary waveform generator, DA: Driver amplifier, MZM: Mach-Zehnder modulator, VOA: Variable optical attenuator, SSMF: Standard single mode fiber, SOA: Semiconductor optical amplifier, PD: Photodiode.

## 3. Experimental investigations

To compare the different modulation formats and DSP schemes, the experimental setup shown in Fig. 2 was used. In the transmitter-side DSP, a pseudo-random multilevel sequence (PRMS) is generated and the bits are mapped on PAM symbols. Afterwards THP with two feedback taps is optionally applied, the sequence is resampled to the AWG sampling rate and a pre-compensation for bandwidth limitations is utilized. The digital signal is fed into the 120 GS/s AWG and the resulting analog sequence is amplified by the driver. The MZM modulates the electrical signal on the optical C-band carrier. The input power into the fiber is controlled by a VOA and, after transmission through the SSMF, the optical signal is amplified by an SOA and detected by a photodiode. Finally, the signal is digitized at 160 GS/s by an oscilloscope and receiver-side DSP is conducted. After the DC-part is blocked, the signal is resampled to two samples per symbol. Afterwards the sampling phase is synchronized to symbol timing and a Volterra nonlinear equalization (VNLE) is applied, using memory lengths of 200, 11, 11 for the first to third order kernels. This high number of equalizer coefficients can be reduced without significant performance degradation, but to avoid individual optimizations for all different cases, we chose to use this sufficiently high number. In case no THP was employed at the transmitter, DFE with two taps is used. Additionally, in case no DFE and THP are used, the VNLE is adapted to yield a duobinary (DB) signal and MLSE is used to decode the DB response. In case THP was applied, the modulo operation $f_{\pm M}$ is applied again to get the PAM sequence back from the EDS. As a last step, the PAM symbols are demapped and the BER is calculated.

Fig. 3 shows the spectra of the received PAM signals before equalization and compares them to the target spectra for the standard PAM and DB signals. In case of PAM4, the high-frequency components of the signal are strongly attenuated and the spectra after both back-to-back and 1 km transmission are closer to the DB target. Therefore, it is expected, that the equalization aiming at the DB signal performs better. For PAM6 and PAM8 the non-DB PAM target is closer to the received spectra, so that this target should lead to better results.

The experimental results for the transmission of 112 GBaud PAM4, 90 GBaud PAM6 and 75 GBaud PAM8 for the back-to-back configuration and a transmission over 1 km SSMF are shown in Fig. 4. As expected, for PAM4 the equalization aiming at the DB signal together with the MLSE outperforms the VNLE + DFE combination aiming at the standard PAM4 signal. THP outperforms DFE for both transmission scenarios and is the best DSP scheme for transmission over 1 km. For PAM6 and PAM8 the equalization aiming at the DB signal shows worse performance than the other schemes, as expected. For both modulation formats, THP does not show any gain over DFE. This meets the expectations in case of PAM8, since the ISI due to bandwidth limitations is comparatively low at a rate of 75 GBaud. However, for PAM6, especially for the transmission over 1 km SSMF, a gain was expected. Also, the performance of THP for PAM4, although good, falls short of the expectations. We identify the reason in the large peak-to-average power ratio (PAPR) of the signal. In the measurements, the same pre-compensation was used for all formats and DSP schemes. However, if THP is used, the PAPR of the signal is enhanced and the additional quantization noise of the digital-to-analog conversion reduces the theoretical gain. The PAPR values of the transmitted

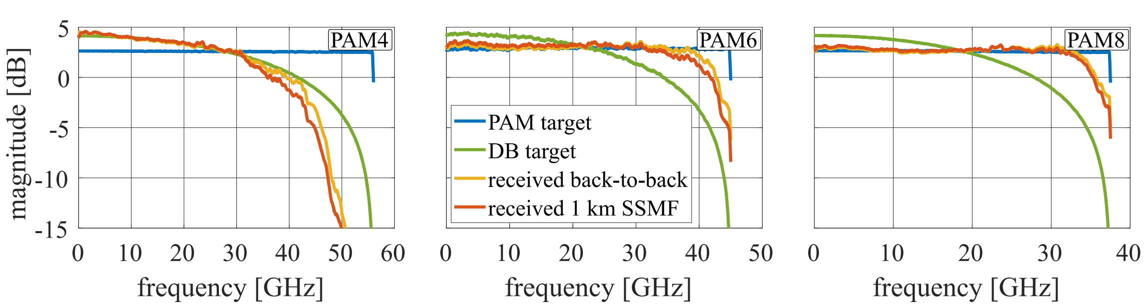


Fig. 3: Received signal spectra before equalization compared to the target spectra of the signals.

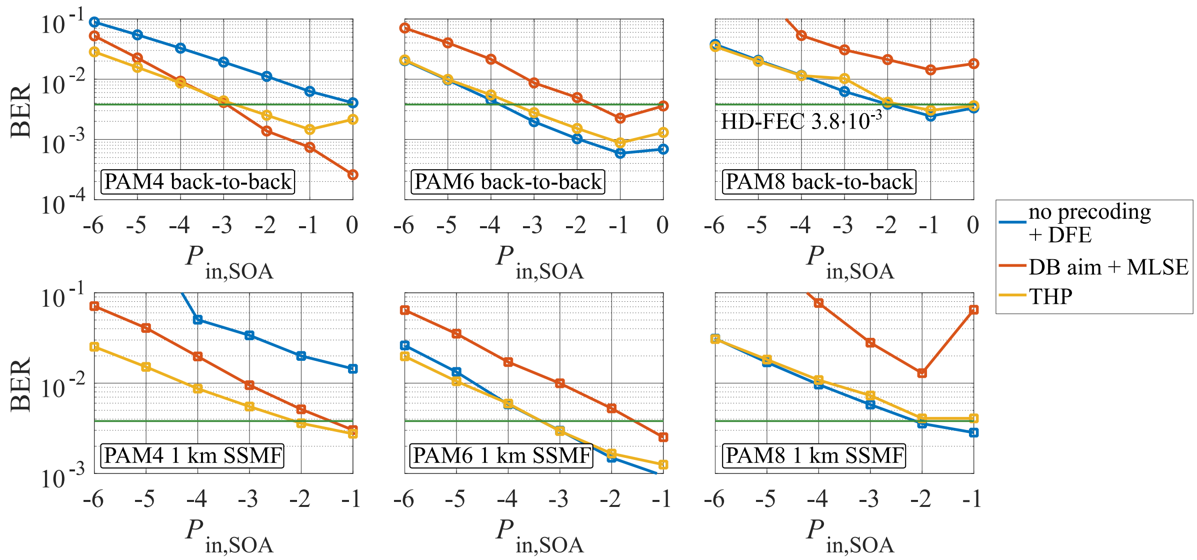


Fig. 4: Experimental results for 112 GBaud PAM4, 90 GBaud PAM6 and 75 GBaud PAM8 using different DSP schemes. The upper three figures show back-to-back results and the lower three results for the transmission over 1 km SSMF.

signals with and without THP after pre-compensation are summarized in Table 1. The PAPR values of the PAM4 and PAM6 signals are significantly increased by THP. In case of PAM8 the impact of THP on the PAPR is not significant.

In the comparison between the PAM formats for optical back-to-back and 1 km transmission, PAM6 shows the best performance. For the transmission without fiber link, the best PAM6 scheme (no precoding and DFE) shows better results than any scheme for PAM4 and PAM8. Only for an input power into the SOA as high as 0 dBm, PAM4 with DB equalizer and MLSE reaches a lower BER. For 1 km, PAM6 shows the best performance for all input power values. In all scenarios PAM8 achieves worse performance than the other PAM schemes.

Table 1: PAPR values of the transmitted signals after pre-compensation.

| | PAM4 | | PAM6 | | PAM8 | |
|---|---|---|---|---|---|---|
| | b2b | 1 km | b2b | 1 km | b2b | 1 km |
| no precoding | 8.36 | 8.36 | 8.14 | 8.14 | 9.17 | 9.17 |
| THP | 8.88 | 9.99 | 9.43 | 9.55 | 9.20 | 9.63 |

## 4. Conclusions

We compared the performance of PAM4, PAM6 and PAM8 for a gross rate of 224/225 Gb/s over up to 1 km of standard single-mode fiber in C-band. For each format, we considered three DSP schemes: a) combination of Volterra equalization and decision-feedback equalization, b) Volterra partial-response equalization with MLSE, and c) transmitter-side Tomlinson-Harashima precoding together with Volterra nonlinear equalization at the receiver. The latter two schemes improved the performance compared to the first one only for PAM4. For PAM6 and PAM8, the approaches a) and c) showed similar performance, whereas approach b) was outperformed. Regarding the modulation formats, PAM6 showed the best results for both back-to-back and 1 km transmission.

## References


[1] N. Stojanovic, C. Prodaniuc, L. Zhang and J. Wei, "210/225 Gbit/s PAM-6 Transmission with BER Below KP4-FEC/EFEC and at Least 14 dB Link Budget," in Proc. ECOC (2018).
[2] J. Wei et al., "Experimental Comparison of Modulation Formats for 200 G/λ IMDD Data Centre Networks," in Proc. ECOC, Tu3D.2 (2019).
[3] Q. Hu et al., "High Data Rate Tomlinson-Harashima-Precoding-Based PAM Transmission," in Proc. ECOC, Tu3D.3 (2019).
[4] Z. Xing et al., "600G PAM4 Transmission Using A 4-Lambda CWDM TOSA Based on Controlled-ISI Pulse Shaping and Tomlinson-Harashima Precoding," in Proc. ECOC, Tu3D.1 (2019).