Optical Multipath Interference Reduction Using Adaptive DC-Removal in High-Speed IM/DD Systems

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Abstract: We present an experimental study of multipath-interference reduction techniques for 56GBd and 92GBd PAM-4. By extending the equalizer with an adaptive removal of intensity fluctuations, MPI tolerance is increased by 2 and 10 dB, respectively.

1. Introduction

The past years have shown that the exponential growth of digital consumption is unstoppable, accordingly the demands on all components in the chain between service provider and end user increase. This results in a rapid adoption of higher data rates, novel all optical systems and lower system margins with increased demands on reliability. A common cause of system failures are reflections, which propagate in a ping-pong fashion between two or more discontinuities and lead to the superposition of attenuated and time-shifted versions of the same signal referred to as multipath interference (MPI). The fundamental nature of MPI is the interferometric phase-noise to intensity-noise conversion, which results in intensity fluctuations of the received signal depending on the delay, attenuation, laser linewidth and state of polarization. The process is well described in [1]. In [2] the authors present a classification of interference phenomena in optical networks and possible mitigation techniques. In the light of continuously tighter system margins, the cancellation and detection of MPI gained recent interest and is considered as the one of the main impairments in high-speed PAM systems [3]–[5]. Even though the return loss of connectors is specified in the range of -40 dB and below, uncleaned connectors can exhibit significantly higher return losses. Further, the use of multiple connectors leads to an accumulation of reflections and thus an increased interference power. In this work, we assume only one interfering signal with purposefully matched state of polarization to provide the worst-case. The experiments present a systematic investigation of MPI effects for an O-band system that transmits 56 GBd and 92 GBd PAM-4 symbols. Based on the results, we propose an adaptive, computationally simple extension of the equalizer (EQ) to effectively suppress the intensity fluctuations and increase the system's tolerance against MPI. After 10 km transmission and 2 km interference delay with signal-to-interference ratio (SIR) of 26 dB, the bit-error-ratio (BER) can be decreased from 1e-2 to 2.5e-3 using the investigated scheme. Additionally, a feed-forward based averaging of the dc-fluctuation is evaluated for comparison.

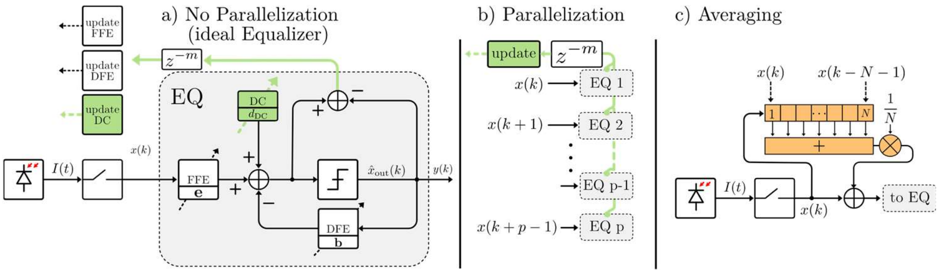

Fig. 1: a) Extension of the FFE and DFE with adaptive subtraction of intensity fluctuations.
b) Parallelization of the EQ with p parallel EQs. c) Feed-Forward based averaging of the signal fluctuation prior to the EQ.

2. MPI Mitigation Using Adaptive DC-Subtraction

Several methods have been proposed to reduce the impact of the MPI on the system, such as line coding [6], high-pass filtering [5], time-domain smoothing [3] or notch filtering in frequency-domain [7]. Another possibility, proposed in this paper, is the extension of the EQ with adaptive subtraction of the intensity fluctuation. In an adaptive EQ, the error ϵ between the equalized signal $\boldsymbol{x}_{in}$ and the decision $\hat{\boldsymbol{x}}_{out}$ is calculated for the FFE and DFE updates as follows

$$\epsilon(k) = \mathrm{d}_{\mathrm{DC}}(k) + \boldsymbol{x}_{\mathrm{in}}(k)\,\mathbf{e}(k) - \hat{\boldsymbol{x}}_{\mathrm{out}}(k)\,\mathbf{b}(k) - \hat{\boldsymbol{x}}_{\mathrm{out}}, \tag{1}$$

where $\mathbf{e}$ and $\mathbf{b}$ are the FFE and DFE filter coefficients, respectively, and d_{DC} is the dc-estimation, that is subtracted from the signal.

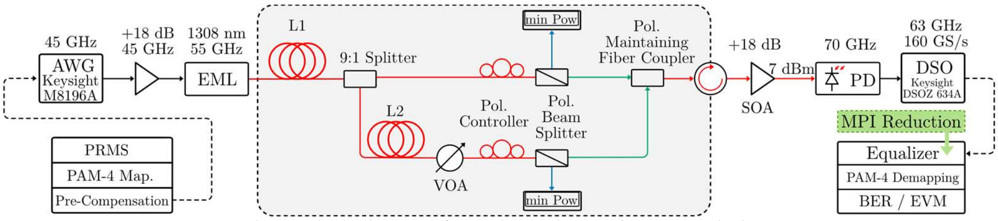

Fig. 2: Block diagram of experimental setup for MPI analysis.

For each update, $\epsilon(k)$ is weighted and subsequently subtracted from $d_{DC}(k)$ as

$$d_{DC}(k+1) = d_{DC}(k) - \mu_{\mathrm{DC}}\,\epsilon(k). \tag{2}$$

This routine involves only two additions and one multiplication. It can easily be implemented in the existing equalizer structure as shown in Fig. 1a). The weight updates cannot be executed in the immediate upcoming clock cycle, as operations for the updates require additional cycles. Hence, the number of clock cycles to process the update, m, is assumed to be $m = 3$.

A main limitation is found in the practical implementation of the algorithm. Typically, the high-speed output of the ADC is fed into a parallelized EQ structure. Assuming a symbol-spaced EQ, the number of required parallel streams, p, is the sample rate of the ADC divided by the ASIC clock rate (see Fig. 1b). This imposes a fixed value for d_{DC} throughout the parallel structure. Which can be written as

$$\begin{aligned} d_{DC}(k+n) &= d_{DC}(k) - \mu_{DC}\,\frac{1}{p}\sum_{n=0}^{p} \epsilon(n), \quad \text{if } p = n \\ d_{DC}(k+n) &= d_{DC}(k), \qquad\qquad\qquad\qquad \text{else} \end{aligned} \tag{3}$$

The update is determined by the cumulated error of the p parallel streams. Usually, if the channel shows a stable transfer characteristic, the parallelization latency does not need to be perceived as a constraint. However, considering the fast dc-fluctuation caused by MPI, the speed of the tracking becomes crucial. These limitations are systematically analyzed in the next section. Another possibility is a feed-forward based smoothing of the signal prior to the EQ, where the dc-fluctuation of the signal is determined as the average over a sliding window of length N (see Fig. 1c). This average value is subtracted from the EQ input signal $x(k)$.

3. Experimental Setup

The components for the experimental setup are shown in Fig. 2. The signal is generated offline, using MATLAB. A pre-compensation is applied to the signal to account for the lowpass characteristics of the hardware components. Consequently, this signal is transferred to the AWG (M8196A). The electrical signal is amplified by an electrical amplifier (SHF 807) and drives an electro-absorption modulator (EML) with 55 GHz bandwidth. The optical signal propagates through 10 km of fiber (L1). To generate the MPI, a parallel branch is used to split out a fraction of the power, passed through another fiber with 1 km length (L2) and attenuated to control the SIR. Finally, the polarization of the two branches is adjusted and the signals are recombined using a polarization maintaining fiber coupler. The setup is comparable to the ones used in contributions [3]–[6]. The receiver consists of a PIN photo diode with a semiconductor optical amplifier (SOA) in front of the photo diode (PD). The SOA has a gain of 18 dB and provides an input power into the PD of 7 dBm. After digitizing the signal, further signal processing is done offline in MATLAB. For all investigated algorithms, the processing steps involve a linear FFE with 25 taps and a 2-tap DFE. Afterwards, the symbols are demapped and the BER is evaluated.

4. Results and Discussion

Fig. 3 shows the four signal levels without equalization (a), with standard equalization (b) and adaptive dc-tracking (c). The fluctuation of the respective PAM levels is significantly reduced, which leads to a BER improvement from 1e-2 to 2.5e-3. In Fig. 4, BER vs. SIR is presented for different equalization schemes and 56 (blue) and 92 GBd (red) symbol rates. Error floors appear due to bandwidth limitations at 1.3e-4 and 2e-3, respectively. In the optimal case ($p = 1$) and an SIR of 25 dB, the presented tracking method significantly improves the BER by a factor of 4 (56 GBd) and almost one decade for 92 GBd. The required SIR to reach the HD-FEC limit of 3.8e-3 improves by 2 dB (56 GBd) and 10 dB (92 GBd). The averaging scheme, which is not dependent on the parallelization and used a window length

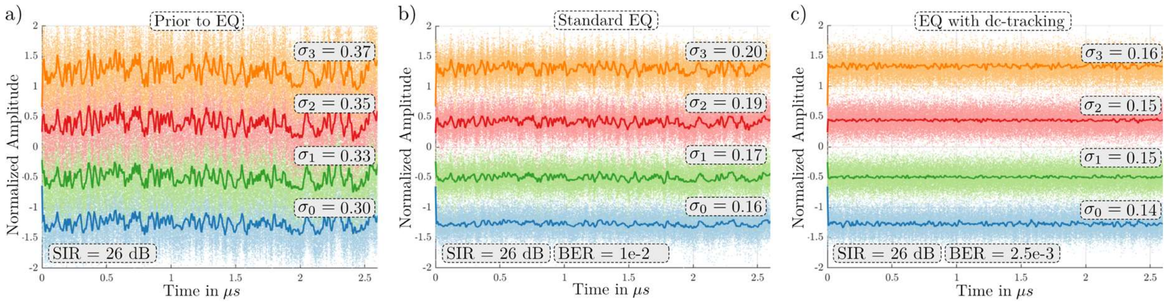

Fig. 3: Signal constellation in time domain. After photodiode and sampling (a), after standard FFE+DFE EQ (b) and after EQ extended with adaptive dc-tracking (c). The SIR is 26 dB.

of $N = 400$, improves the performance of the EQ for high MPI levels. For low values of MPI, the scheme is not superior to the standard EQ, the error-floor of the 56 GBd signal is even raised. Introducing a parallelized structure ($p = 92$), the performance of the dc-tracking diminishes. This is evaluated in Fig. 4b), where the required SIR to reach the FEC limit is shown for different degrees of parallelization. Again, the 56 GBd signal shows higher resilience against MPI. As expected, the parallelization has a negative effect on the tracking performance. At 56 GBd, the algorithm does not improve the standard EQ, if $p > 35$. Moreover, for $p > 10$, the feed-forward based averaging scheme is beneficial. For 92 GBd, the dc-tracking algorithm shows an improvement for all p values; however, for $p < 45$ the benefit is constantly improving with every step towards $p = 1$.

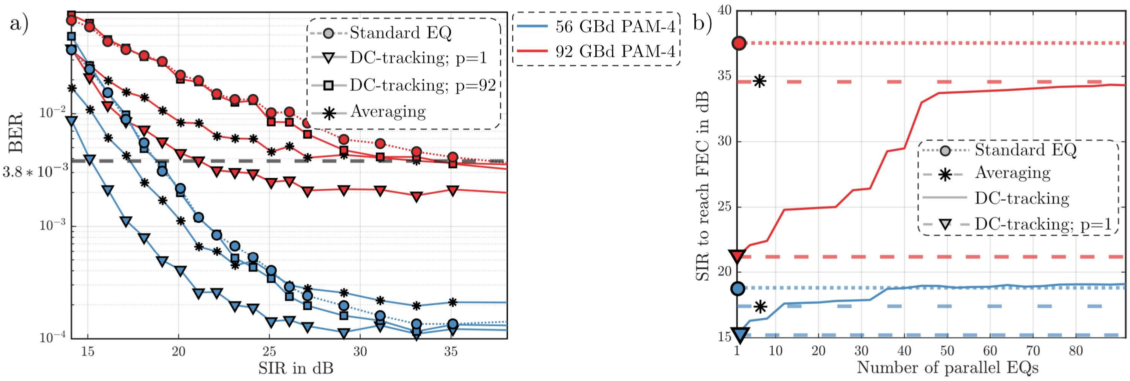

Fig. 4: BER of 56 GBd and 92 GBd PAM-4 signals for different SIR conditions is shown in 4a), SIR to reach the FEC limit is shown in 4b). The standard EQ, the optimal tracking (p=1), a parallelized strcuture (p=92) and the averaging scheme are analyzed.

5. Conclusion and Outlook

Compared to the averaging approach, the adaptive algorithm is superior, if the speed of the coefficient updates can be kept high. A possibility would be the use of an ASIC with higher clock rate, although this is possible only within a limited range. Thus, further steps involve the analysis of DSP structures to reduce the number of parallel EQs. Altogether, the extension of the FFE and DFE with a simple dc-tracking and subtraction algorithm presents an efficient solution to increase the system performance in the presence of MPI.

6. References

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