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Improved Pre-Compensation to Combat Power Fading in IM/DD Systems

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Abstract *We propose a pre-compensation approach allowing an improved compensation of spectral nulls caused by CD-induced power fading in IM/DD systems. We show a gain by the proposed scheme in 35 km PAM4 C-band transmission experiments at rates in the order of 50 GBd. ©2022 The Author(s)*

Introduction

Although coherent systems push forward into a growing number of applications, intensity-modulation/direct-detection (IM/DD) still provides a better cost effectivity for several short-reach scenarios, such as intra-datacentre communications. Due to the ever-increasing data traffic, the required symbol rates in IM/DD systems are continuously growing. Thus, chromatic dispersion (CD) and the resulting power fading after DD become a more and more severe impairment. The options to compensate CD in DD systems are limited. While the deployment of dispersion compensating fibre is too costly for short-reach applications, effective electronic dispersion compensation (EDC) in the transmitter digital signal processing (DSP) is only applicable at the cost of a more complex modulator, i.e. IQ modulator [1,2] or dual-drive Mach-Zehnder modulator (MZM) [3]. Single-sideband signals, which are e.g. used in self-coherent systems, can avoid power fading, but their generation requires additional hardware [4-6].

Recently, an approach to mitigate the effect of CD in systems using simple IM has been proposed [7,8]. However, it is based on a computationally complex iterative process to prepare the signal for the transmission over the dispersive channel.

In this paper, we propose a pre-compensation scheme, that limits the impact of CD in IM/DD systems. This scheme applies a simple transfer function, that amplifies specific frequencies in the transmitted signal in order to allow a better reconstruction of the spectral nulls induced by power fading in the receiver DSP. We show a performance gain in 35 km C-band PAM4 transmission with rates between 42 GBd and 52 GBd.

Proposed Approach

The proposed pre-compensation is based on the fact, that redundant information is transmitted for signals with an oversampling factor $n_{\mathrm{OS}} > 1$. Fig. 1 visualizes this for a 50 GBd signal, that is up-sampled by a factor of two and shaped with a root-raised cosine (RRC) filter with a roll-off factor (ROF) of one. The signal after oversampling covers twice the spectral range of the initial signal. However, as the information contained in the signal originates from the same source, redundant information is contained in the oversampled signal. More exactly, a pair of frequencies separated by the symbol rate contains the same information. Therefore, the areas marked in the same colour are redundant. If now a frequency $f_{\mathrm{null},n}$ corresponds to the n^{th} spectral null caused by power fading, a redundant frequency $f_{\mathrm{r},n}$ containing the same information can be found. The relationship of these frequencies can be expressed as

$$f_{\mathrm{r},n} = \begin{cases} f_{\mathrm{null},n} + f_{\mathrm{sym}}, & \text{if } f_{\mathrm{null},n} < 0 \\ f_{\mathrm{null},n} - f_{\mathrm{sym}}, & \text{else} \end{cases}, \tag{1}$$

where f_{sym} is the symbol rate. Instead of focusing on the frequencies that are cancelled by power fading, the idea of the proposed selected-frequency pre-compensation (SFPC) is to amplify the redundant frequencies $f_{\mathrm{r},n}$ in the transmitter

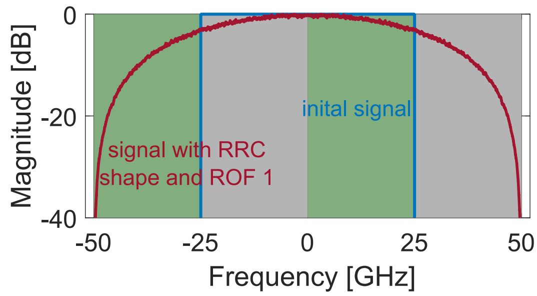

Fig. 1: Visualization of the spectra of a 50 GBd signal at symbol rate and after twofold up-sampling and shaping with an RRC filter. The areas marked in the same color contain the same information.

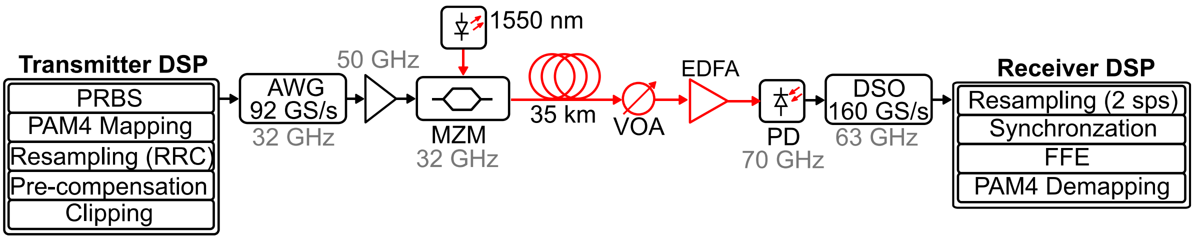

Fig. 2: Experimental setup including transmitter and receiver DSP. The bandwidth limitations are given below/above the components.

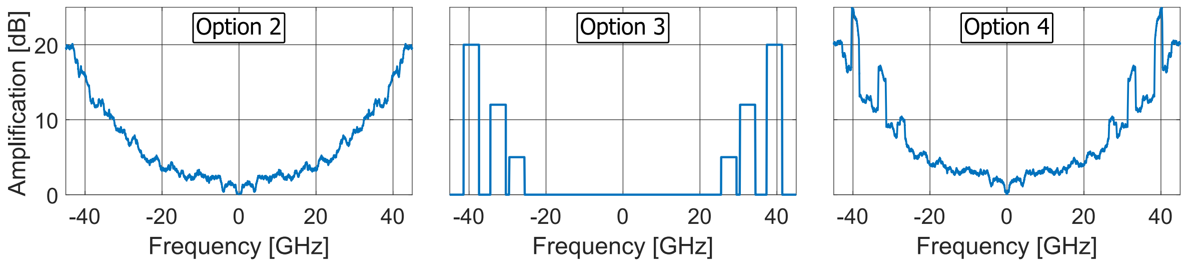

Fig. 3: Exemplary frequency responses of pre-compensation options 2 - 4 according to Tab. 1 for a 50 GBd signal.

DSP. Therefore, knowledge about the positions of the spectral nulls for the channel needs to be available at the transmitter. The pre-compensation needs to be combined with an equalizer in the receiver DSP, that operates at a sufficiently high oversampling. If $f_{\mathrm{r,max}}$ is the highest redundant frequency corresponding to the first spectral null inside the signal spectrum caused by power fading, the required oversampling is given by

$$n_{\mathrm{OS,eq}} \geq \frac{f_{\mathrm{r,max}}}{f_{\mathrm{sym}}}. \tag{2}$$

In this case, the spectral nulls can be partially recovered using the redundant information. As not only the exact frequency of the spectral null, but also frequencies around it are attenuated significantly by power fading, it is advantageous to amplify a certain range of frequencies. The optimization of the SFPC response, i.e. the amount of amplification as well as the width of the amplified frequency range is still an open problem. For the results shown in the next section, the optimization is done by sweeping through possible values and determining the optimum based on the resulting bit error ratio (BER).

Tab. 1: Considered options for pre-compensation. IBPC: inverse bandwidth pre-compensation, SFPC: selected frequency pre-compensation

Option	Pre-compensation
1	none
2	IBPC
3	SFPC
4	SFPC + IBPC

The SFPC can be combined with conventional inverse bandwidth pre-compensation (IBPC), which improves the performance in systems that are subject to narrow bandwidth constraints and CD.

Experimental Investigations

The approach is experimentally investigated using the setup shown in Fig. 2. In the transmitter DSP, digital data is generated and mapped on PAM4 symbols. The signal is re-sampled to the digital-to-analogue converter (DAC) sampling rate and shaped by an RRC filter. The ROF is given by

$$\beta = \begin{cases} f_{\mathrm{DAC}} / f_{\mathrm{sym}} - 1, & \text{if } f_{\mathrm{DAC}} < 2 f_{\mathrm{sym}} \\ 1, & \text{else} \end{cases}. \tag{3}$$

Afterwards, pre-compensation is applied. For this step, the options summarized in Tab. 1 are considered. Finally, the signal is clipped. An analogue signal is generated by the arbitrary waveform generator and after amplification, a Mach-Zehnder modulator is used to modulate the signal on the optical C-band carrier. After transmission over 35 km SSMF, an EDFA is used to provide a constant input power of 7 dBm into the photodiode. The analogue signal is converted into a digital signal by a digital storage oscilloscope and receiver DSP is performed. After re-sampling to two samples per symbol, the signal is synchronized and feed-forward equalization (FFE) is applied at the same oversampling rate. For FFE, a Volterra nonlinear equalizer with memory lengths of 200, 11, 11 for the first to third order is used. Finally, the PAM4

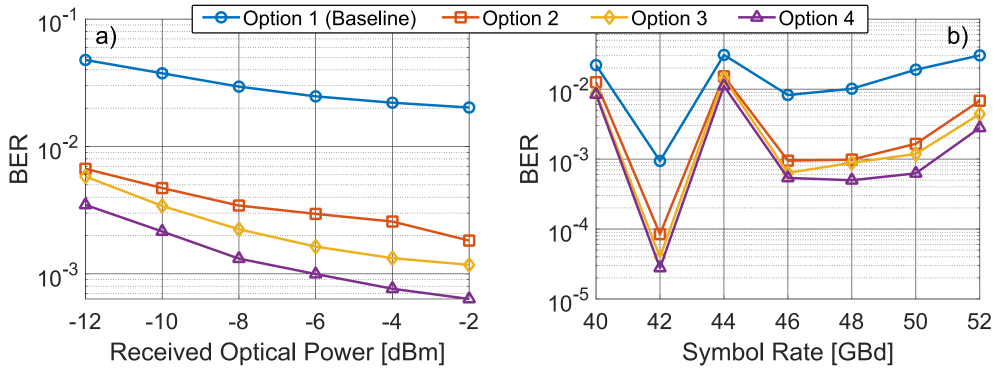

Fig. 4: Experimental results for the comparison of the different pre-compensation options according to Tab. 1. a) shows BER in dependence on the input power into the EDFA for 50 GBd PAM4 transmission and b) shows the performance for PAM4 with varying symbol rates.

symbols are de-mapped, and the BER is calculated.

Exemplary frequency responses for the pre-compensation options 2 - 4 according to Tab. 1 are depicted in Fig. 3. For IBPC, the maximum amplification is optimized individually with respect to the resulting BER. For SFPC, the height and width of the amplification bins are optimized, while an optimization of all the aforementioned parameters is done for the combination of SFPC and IBPC.

The results for a transmission of 50 GBd PAM4 over 35 km SSMF are shown in Fig. 4 a). The received optical power (ROP) refers to the input power into the EDFA. While the performance without pre-compensation is relatively poor, IBPC (option 2) can achieve a significant improvement. However, focusing only on the redundant frequencies to overcome the spectral nulls (option 3) leads to a better performance for all ROPs. Finally, combining SFPC and IBPC (option 4) brings an additional gain in performance.

Results for varying symbol rates at a constant ROP of -2 dBm are shown in Fig. 4 b). In general, the same order in terms of performance as in Fig. 4 a) can be observed. However, significant differences for the performance of all schemes can be observed in dependence on the symbol rate. While all pre-compensation options perform well at 42 GBd, the results show a poor performance for 40 GBd and 44 GBd. This can be explained by the positions of the spectral nulls and the redundant frequencies. In order to reconstruct a spectral null $f_{\mathrm{null},n}$, the corresponding redundant frequency $f_{r,n}$ needs to be available in a sufficient quality at the equalizer. At certain combinations of symbol rate and accumulated CD, one or more redundant frequencies can be subject to power fading themselves. In this case, no information is available to reconstruct the spectral nulls. Tab. 2 summarizes the positions of the reconstruction frequencies relative to their nearest spectral null for 42 GBd and 44 GBd. For 42 GBd, the gaps are wider than 1 GHz and therefore the reconstruction frequencies are not severely attenuated by power fading. As a result, a good overall performance can be achieved. For 44 GBd on the other hand, the gaps are very small and the reconstruction frequencies are therefore strongly attenuated. This explains the poor performance for this symbol rate.

Tab. 2: Positions of the reconstruction frequencies relative to their nearest spectral null for 42 GBd and 44 GBd.

Symbol Rate [GBd]	Gap between reconst. freq. and nearest spectral null [GHz]	
	1st null	2nd null
42	1.43	1.95
44	0.31	0.07

Conclusions

We introduce selected-frequency pre-compensation (SFPC) to mitigate the impact of CD-induced power fading in IM/DD systems. SFPC relies upon the presence of redundant frequency components in oversampled signals. The scheme is based on amplifying specific frequencies in the transmitted signal. Experiments for the transmission of 40 GBd to 52 GBd PAM4 over 35 km SSMF show an improved performance compared to conventional inverse bandwidth pre-compensation. However, a drawback is given by the fact, that the scheme cannot work properly for certain combinations of symbol rate and accumulated CD in the channel. Solving this issue is a topic for future research. A potential solution could be tuning of the modulator chirp to avoid the scenarios at which SFPC is not effective.

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