Link Segmentation Based Nonlinearity Reduction using Fibers with Shifted Dispersion Zero for Datacenter Networks

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Abstract *We propose a novel solution to mitigate FWM interference using link segmentation by slightly shifting the dispersion zero. 2 and 10 km links with 1.6 Tb/s data-rates were simulated using eight O-band channels carrying 112 Gbd PAM-4 signals. A comparison with polarization interleaving is done.*

Introduction

In recent years, the growth of datacenters has been nothing short of staggering. According to recent studies, global datacenter traffic has been increasing at an average annual rate of 25% since 2017. Together with the trend for flatter network architectures, data rates of 1.6 Tb/s are targeted in the near future. Intensity modulated / directly detected (IM/DD) systems with pulse amplitude modulation (PAM) are widely used due to cost and system advantages. Here, the link capacity is determined by three degrees of freedom namely the number of bits per transmitted symbol, the symbol rate per channel, and the number of parallel WDM optical channels. Digital signal processing (DSP) algorithms are developed to push further the limitations on each of these aspects. Unfortunately, a typical transceiver pluggable attributes almost 50% of the energy consumption to the DSP to compensate main limiting factors in IM/DD systems, e.g., bandwidth limitations and chromatic dispersion [1].

Transmitting in the O-band, where, despite an increased link loss, the chromatic dispersion is significantly reduced, relaxes the dispersion penalty [2], [3]. However, the spectral proximity between the signal energy and the zero-dispersion wavelength (ZDW) gives rise to nonlinear four-wave mixing (FWM) interferences. Especially future 1.6 Tb/s systems, which presumably use eight channels at 200 Gb/s each, need a careful assessment of the interdependences in the near ZDW region to find suitable solutions. Several mitigation techniques were described, such as unequal channel allocation, launch power reduction, and polarization interleaving. Drawbacks of these schemes are increased dispersion penalties for the outer channels, the need for additional amplification at the receiver or increased receiver sensitivity and a weak tolerance against polarization mode dispersion (PMD), respectively.

In this work a novel solution to overcome the FWM problem is presented. We use a segmented fiber link with fiber segments having slightly shifted dispersion zeros. Besides reducing FWM, the proposed solution also limits the accumulated dispersion when the ZDW of the used fiber is symmetrically shifted up- and down, respectively. The proposed technique achieves better results than the polarization interleaving schemes.

Theory and Proposed System Architecture

FWM results in the generation of new frequency components, if energy is co-propagating on several wavelengths. The relation of the resulting fourth frequency is given by $\omega_{FWM} = \omega_i + \omega_j - \omega_k$, where i, j, k are the indices of the three generating wavelengths ω. Generally, in a WDM system with N evenly spaced channels, the number of FWM products is given by the combinatorial expression $M = (N^3 - N^2)/2$, which results in $M = 24$ and $M = 224$ products for four and eight channels, respectively [4]. The power of the FWM products is strongly dependent on the optical power, the

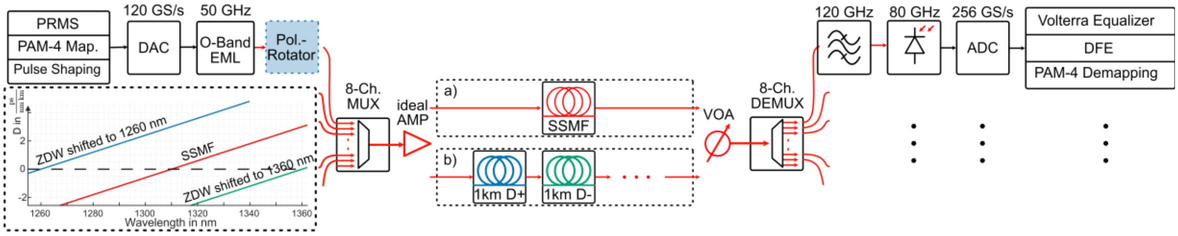

Fig. 1: Setup of the IM/DD WDM transmission system used for the simulative investigations. The inset shows the dispersion evolutions of the used fiber types. The SSMF link is shown in a). The proposed segmented link is shown in b).

fiber nonlinearity, the state of polarization, and the channel position. This is captured by the FWM efficiency η_{FWM} and the phase matching condition $\Delta\beta$ [5]. The phase matching condition approaches zero, if the states of polarizations (SOP) remain fixed and are the same for all channels, and the channels are near the ZDW (O-band), which in turn leads to an increased FWM efficiency [6]. Although the impact of PMD in short-reach transmission systems is limited, its influence on FWM efficiency can be significant.

To provide a careful separation of the investigated phenomena, we define a worst case, where:

- 8 WDM channels are on a fixed, dense grid,
- the ZDW is between channels 4 and 5,
- the transmission system has a high launch power.

The resulting channel plan is symmetrically aligned around the ZDW being at 1310 nm and has 400 GHz channel spacing. The channel positions are depicted in Fig. 2. As shown in [7], the probability of a worst case ZDW alignment is in the range of 0.5% even for 4 channels and remains constant for a deployed link.

The segmentation of a fiber link into several fiber pieces of equal lengths (with slightly different ZDWs) can be beneficial for several reasons. First, the FWM interference will be significantly reduced: even if the fiber is of the same type, deviations within and between the production batches are present and even small fluctuations in core diameter and circularity lead to deviations in the optical properties i.e., the exact position of the ZDW. This can be exploited as an advantage. It is shown in [5], that the FWM efficiency of a segmented fiber link is lower than that of the individual fiber pieces. Next, if the proximity between the channels and the ZDW is sufficiently large, FWM interferences can be reduced to take negligibly small values similar to the performance in C-band [5].

We assume the ZDW of the respective segments

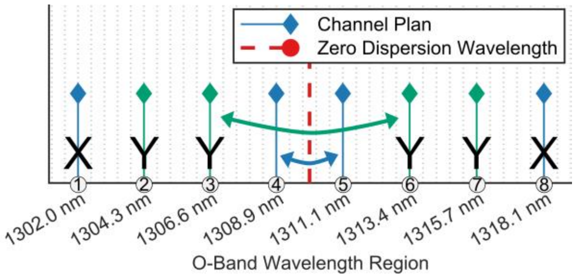

Fig. 2: WDM channel plan with 400 GHz spacing between eight channels. The paired polarization scheme (X YY XX YY X) is visualized, here the polarization states are point symmetric w.r.t. ZDW.

to be shifted by $\pm$50 nm, which can physically be achieved by varying the fiber core diameter [8]. As a result, the two fiber types have ZDWs at 1260 nm (D-) and 1360 nm (D+). Assuming a dispersion slope of $S = 0.6\ \frac{\mathrm{ps}}{\mathrm{nm\ km}^2}$, it is straight-forward to show that the accumulated dispersion after one D+ segment is larger than in the SSMF case. However, the propagation through the second D- segment represents a dispersion compensation. After propagation through the two segments of length n, CD will accumulate like in the case of $2n$ km of SSMF and is thus directly comparable.

Simulation Setup

The performance of the 8-λ O-band transmission system is investigated using numerical simulations in MATLAB. The corresponding setup is shown in Fig. 1. In the transmitter DSP, eight random data streams are generated and mapped on PAM-4 symbols with a symbol rate of 112 GBd, for the statistical analysis these streams are generated differently for each simulation in a simulation batch. Then the signal is resampled and shaped using a root-raised-cosine pulse. The electrical bandwidth of the DAC is 56 GHz (3^{rd} order Bessel filter) and the sampling frequency is set to 120 GS/s. Next, the signals are modulated using an electro-absorption modulated laser (EML) with a cosine-shaped transfer characteristic and 50 GHz

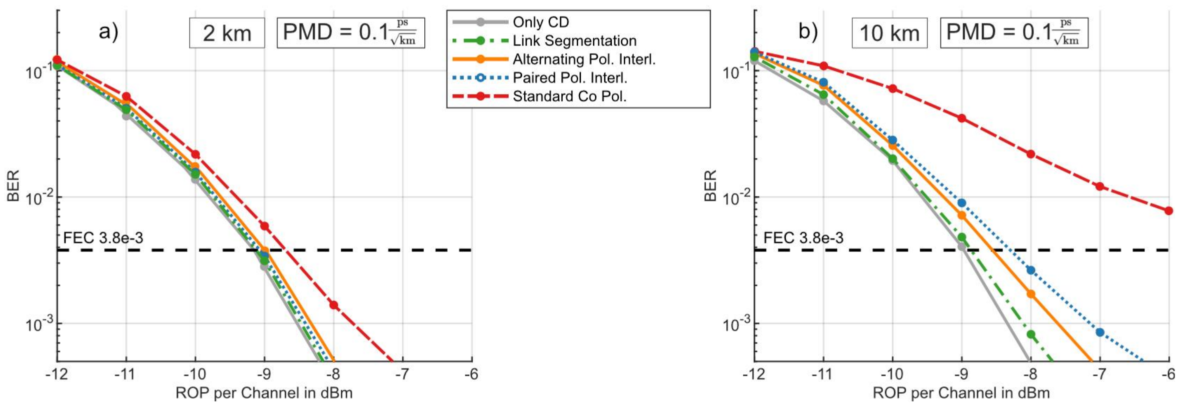

Fig. 3: BER performance of the different schemes for 2 km and 10 km simulation in the defined worst-case scenario.

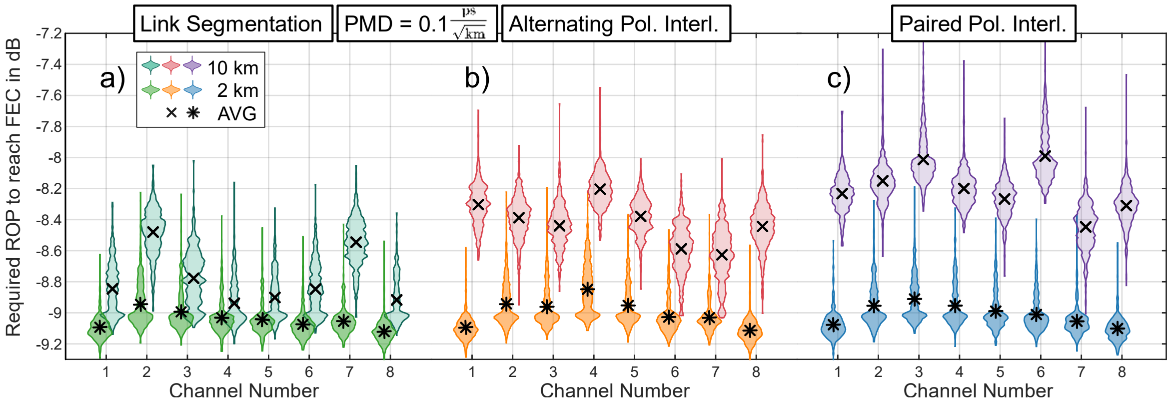

Fig. 4: Required ROP to reach the FEC threshold for the different schemes at 2 km and 10 km with ZDW between channels 4 and 5. The average value is marked for each channel for 2km ($*$) and 10km ($\times$).

electro-optic bandwidth. The optical channels are (de-) multiplexed by an ideal (de-) multiplexer without insertion loss. Before transmission, the total field representation of the signal is again up-sampled. At this point each symbol is represented by 512 samples. The shown amplifiers are assumed to be noise-less and scale the signal ideally to set different launch power values. The launch power is 3 dBm per channel in all cases. The optical propagation is calculated by solving the coupled-nonlinear Schrödinger equation (CNLSE) with the symmetrized split-step Fourier method (SSFM). PMD is simulated using the waveplate model with 100 waveplates per km. The photodiode has an electrical bandwidth of 80 GHz and introduces thermal noise, shot noise and dark current. At the ADC, the signals are sampled at two samples per symbol. A nonlinear Volterra equalizer with 50 linear taps and a memory length of 9 for both the second and third order followed by a decision feedback equalizer with two taps were used. To gain a systematic insight into the interplay between FWM and PMD, a CD-only simulation ($\gamma = 0$; $PMD = 0\,\frac{\mathrm{ps}}{\sqrt{\mathrm{km}}}$) was performed as baseline. For the link segmentation, the segment length is set to 1 km. Two proposed polarization interleaving schemes, the alternating polarization (XYXYXYXY) and the paired polarization (YXXYYXXY) were simulated [9]. For PMD simulations the PMD parameter was set to $0.1\,\frac{\mathrm{ps}}{\sqrt{\mathrm{km}}}$, and 500 realizations were carried out for the respective techniques.

Results and discussion

In Fig. 3 a) the BER after 2 km is depicted for the investigated schemes using a launch power of 3 dBm in the presence of PMD. In the defined worst-case scenario, the standard scheme is deteriorated by FWM. While the proposed scheme shows the best performance, also the other mitigation schemes show a sufficient performance; almost no penalty w.r.t. the CD only simulation is visible. In the 10 km case of Fig. 3, it becomes evident that the polarization interleaved schemes are affected by PMD. Compared to the CD-only simulation, an average penalty of 0.2 dB, 0.5 dB and 0.7 dB is visible for the segmentation, alternating- and paired interleaving schemes respectively. The standard, co-polarized scheme shows a significant penalty. The difference between the polarization schemes in this simulation can be explained by the location of the ZDW, which lies exactly between channels 4 and 5 and results in a non-degenerate mixing of the symmetric channels to the left and right of the ZDW. These symmetric channels are parallelly polarized for the paired interleaving (= large η_{FWM}) and perpendicularly polarized for the alternating interleaving (= low η_{FWM}). A channel-wise analysis is depicted in Fig. 4, where the required ROP to cross the FEC limit is shown for each channel and scheme. The violin plots show a kernel density estimation of the 500 PMD realizations, the average value is marked. The visualization clearly shows, how a few extreme cases shift the mean value from the mode value of the density function. The fiber segmentation scheme is slightly advantageous for all channels in this worst-case scenario. Looking at 10 km, the difference between polarization interleaving and fiber segmentation becomes evident. In fact, only channels 2 and 7 of the segmentation scheme experience a more significant degradation.

Conclusions

The proposed scheme always shows superior results w.r.t. other mitigation techniques. In the 10km case, a significant reduction of the FWM nonlinear interference has been achieved. Finally, using the segmented fiber scheme could allow denser channel spacing and/or higher channel count systems. Future investigations will consider the performance benefits for a realistic ZDW distribution instead of a fixed worst-case.

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