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Robust Upgradeable Rate-Adaptive Probabilistic Balanced SOP Transmission for Dispersion Managed Links

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Abstract *A probabilistic signaling technique with balanced state of polarization is introduced and its performance is analyzed for coherent dispersion-managed links. Simulation results show stable gains over the number of employed spans and a positive effect on WDM channels already before upgrade. ©2022 The Author(s)*

Introduction

Not all signals suffer from the Kerr effect in the same way and Civelli et al.[1] preselect symbol sequences that based on heuristic observations of the channel collected the least non-linearities. This approach trades rate against signal degradation. A structured encoding may decrease the complexity of this approach. Shiner et al. outline the role of state of polarization (SOP) for the non-linear Kerr effect[2]. They consider two consecutive dual polarization (DP)-QPSK symbols in time, i.e., eight dimensions (8D) and use only combinations for which the Stokes vectors of both symbols add up to the all zero vector.

We evaluate 8D constellation points according to their capability to avoid non-linear signal degradation based on[2]. This information is combined with a probabilistic amplitude shaping (PAS)[3] signaling scheme and builds a probabilistic balanced SOP (PBSOP) transmitter with manageable complexity. It can trade transmission rate against non-linear signal degradation as in[1]. This contribution extends results presented in[4]. Simulations for dispersion-managed links (DMLs) with large effective area fiber (LEAF) and standart single mode fiber (SSMF) show that the gains obtained in terms of observed SNR are stable over multiple spans. Furthermore, PBSOP improves legacy links in an upgrade scenario.

Balanced State of Polarization

The SOP can be described by Stokes vectors and indicates how non-linearities affect a signal that propagates through optical fiber. If the Stokes vectors of consecutive symbols point into the same direction, the non-linearities accumulate quickly in that direction, which leads to a strong degradation of the signal. On the contrary if the Stokes vector of consecutive vectors are opposite, the resulting nonlinearities have a strong high-frequency component that is filtered by the low-pass transfer function of the XPM efficiency term. This observation was made in[2]and the approaches in[2],[5],[6] consider two constrained consecutive DP-QPSK symbols to obtain a balanced SOP bi-symbol.

Consider the Stokes vector of one DP-QPSK symbol. The second Stokes parameter is always zero and the intensity is always the same. Therefore, the angle between constellation points on X- and Y-polarization to describes the stokes vector completely and we can classify the two consecutive symbols by the difference of two of those angles, i.e.,

$$\delta = (\angle(X_1) - \angle(Y_1)) - (\angle(X_2) - \angle(Y_2)), \quad (1)$$

where X_i and Y_i represent the i-th constellation point on the X- and Y-polarization and the $\angle(\cdot)$ operator returns the angle of a constellation point. For QPSK, δ may take on the values $[0, \pi/2, \pi, -\pi/2]$. For $\delta = 0$ both Stokes vectors point in the same direction, $\delta = \pi$ indicates that both Stokes vectors point in the opposite direction and $\delta = \pm\pi/2$ means that the vectors are orthogonal to each other and the sign preserves the order. This divides the 8D QPSK constellation into 4 different classes of 64 constellation points with similar SOP properties. In[5] the authors use consecutive symbols with $\delta = \pi$, i.e., only 64 out of 256 8D points are used implying a rate of 3/4. Bendimerad et al. extend this approach and allow 8D constellation points with $\delta = \pm\pi/2$ and a rate of 7/8[6]. The constellations are called PB-8D-64 and PA-7B8D, respectively.

Probabilistic Balanced SOP

Both PB-8D-64 and PA-7B8D limit the 8D constellation to trade rate for nonlinear tolerance.

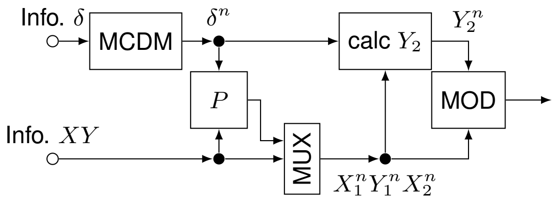

Fig. 1: PBSOP transmitter including a forward error correction code

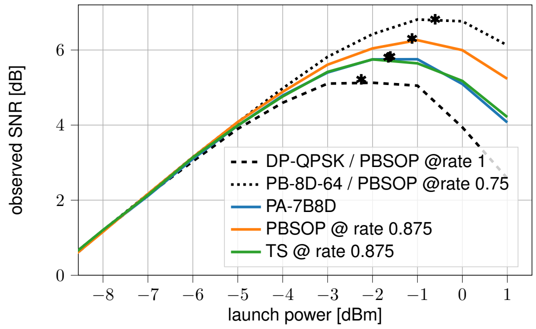

Fig. 2: Power sweep over a 60-span link for the extreme cases of DP-QPSK and PB-8D-64 and for 3 intermediate solutions with rate 7/8

Schulte et al.[4] use the unconstrained 8D space and reduce the occurrence probability of less favorable 8D symbols. This way it is possible to use constellation points with $\delta = 0$ very rarely and not never.

PAS[3] is a coded modulation technique that enables energy efficient signaling. In a nutshell, a distribution matcher encodes information into symbols with a desired distribution. A systematic forward error correcting code (FEC) protects these symbols and the parity bits are interpreted as signs and the unequally distributed symbols as amplitudes. The distribution matcher can be adjusted for the required rate and distribution. We are interested to generate 8D constellation points with a specific δ and in a second step to impose a distribution on δ. According to (1), we can choose 3 out of 4 constellations points freely, i.e., only the fourth constellation point determines to which of the 4 SOP classes the 8D-symbol belongs. In other words, we can uniquely define a constellation symbol by X_0, Y_0, X_1, δ. Since X_0, Y_0 and X_1 can be chosen freely, i.e., without restriction on their distribution, they can also contain parity bits. PAS can be combined with minimum cost distribution matching (MCDM)[7]. MCDM orders sequences according to a per-letter cost function. For energy-efficient signaling, the cost of a symbol may correspond to the squared amplitude of a constellation point. In this work, we assign the costs $[2, 1, 0, 1]$ to the 8D symbols with angles $\delta = [0, \pi/2, \pi, -\pi/2]$, respectively. Please note that the MCDM can be replaced by any distribution matcher and the family of target distributions then is[7]:

$$P(a) \sim \exp(-\nu c(a)) \tag{2}$$

where $c(a)$ is the cost of the letter a nd ν is a free positive parameter of the distribution family that controls the rate.

Fig.1 shows the block diagram of the PBSOP transmitter. A MCDM encodes information into a sequence δ^n. δ^n and a secondary information stream XY are protected via a systematic forward error correction code. The parity bits are generated in the matrix multiplication with P. Parity bits and information XY form $X_1^n\ Y_1^n\ X_2^n$. Recall, that we could choose them freely. If the first inequality is fulfilled then the $X_1^n Y_1^n X_2^n$ contains only parity bits, wheres the FEC code generates no parities if the second inequality is fulfilled. This leads to an uncoded transmission. The missing second Y-polarization Y_2^n is calculated symbol-wise via (1). The MCDM rate controls the relative frequency of δ. For a MCDM rate of 0, δ is deterministic, i.e., always π. This leads to the least signal degradation and recovers PB-8D-64. For the maximum rate, i.e. 2 bits per 8D symbol, δ is uniformly distributed and we recover DP-QPSK signaling. In-between, we have a fine control over the rate. As a term of comparison, we consider a time-sharing (TS) signaling scheme of DP-QPSK and PB-8D-64 with interleaving. The TS rate can be varied by changing the ratio between the modulations, e.g., we may obtain a rate of 7/8 by using half of the time DP-QPSK and PB-8D-64, respectively.

Simulation Setup and Discussion

Eight wavelength-division multiplexed (WDM) dual-polarization channels are generated at the transmitter. Each channel carries 2^{13} symbols. Signals are oversampled at 40 samples/symbol, and modulated at a baudrate of 120Gbaud with a root-raised cosine (RRC) pulse shape with a roll-off factor of 0.25. We multiplex all channels on a 150GHz grid and at the receiver evaluate the 5th channel. The optical signal at the output of the multiplexer is launched into the optical link. We simulate link lengths of 10, 20, 30, 40 and 60 of 75km where the longest configuration was motivated by[6]. We compare results for SSMF and LEAF in dipersion managed spans which are combined with an ideal 100% in-line dispersion compensation fiber (DCF) and a noiseless flat-gain in-line amplifier. The polarization mode dispersion (PMD) of the fiber is not considered. The sequence is repeated 100 times and

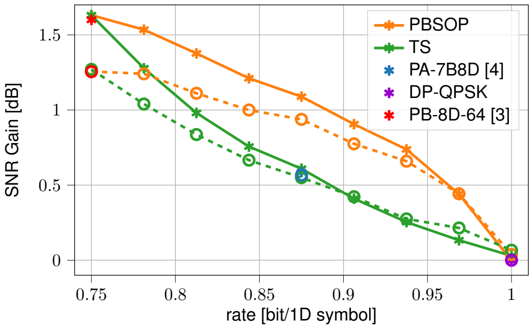

Fig. 3: SNR gain vs transmission rate over DP-QPSK for LEAF[solid,stars] and SSMF[dashed, circles].

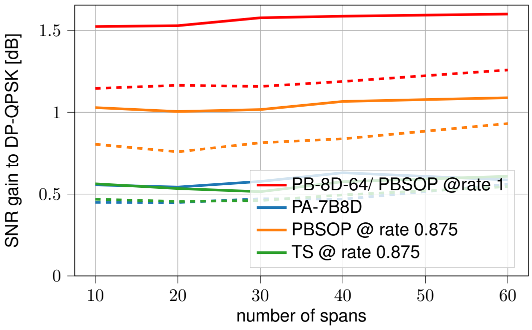

Fig. 4: SNR gains compared to DP-QPSK for LEAF(solid) and SSMF(dashed) over number of spans

in front of the receiver, additive white Gaussian noise (AWGN) is loaded to the signal assuming a noise figure (NF) of the amplifiers of 7dB. Furthermore, we account for phase noise of the lasers with 10 kHz linewidth. At the receiver, an RRC matched filter is applied to the digitized signal of the 5th channel, followed by a data-aided carrier phase recovery. Finally, the observed signal-to-noise ratio (SNR) is estimated. The observed SNR indicates the strength of non-linear effects. Modulation, demodulation, and coding are purposely idealized to isolate the nonlinear gain of the considered signaling scheme. We sweep the launch power per channel from -10 to -3 dBm and estimate the optimal launch power fitting all observed data points to the GN model[8].

In Fig.2 we show a power sweep for different modulation formats over observed SNR and the black stars indicate the estimated maximum. DP-QPSK and and PB-8D-64 have rates 1 and 0.75, respectively and coincide with the performance of the transmission scheme at the extreme rates. The remaining three curves show the performance of PA-7B8D, TS and PBSOP with rates 7/8 bit/real dimension. Note that PA-7B8D and TS have the same SNR gain. This is consistent with our assumption on the per-letter cost function, since both approaches have an average cost of 0.5 per symbol. Furthermore, PBSOP improves upon the other strategies by a gain of ~ 0.5 dB.

Fig.3 shows the observed maxima for PBSOP,

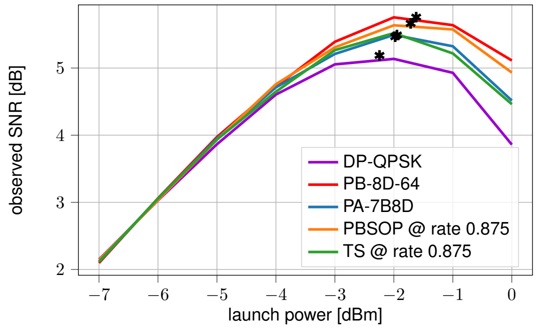

Fig. 5: Power sweep over a 60-span link for upgrade scenario

TS, PA-7B8D, PB-8D-64 and DP-QPSK collected over different rates and fiber types. To this end we performed power-sweeps and collected the respective maxima. Since PA-7B8D, PB-8D-64 and DP-QPSK are not rate adaptive, they are represented by single points. the performance coincides for the respective schemes at rates 0.75 and 1 bit/real dimension and PBSOP outperforms TS for all other rates. While the maximum difference between TS and PBSOP is reached at a rate around 7/8 bit/real dimension, it is worth to note that the greatest slope can be found for rather high rates which might serve as working points. Fig.4 shows the observed SNR gain compared to DP-QPSK for different numbers of spans and different fiber types. This indicates a robust gain of the signaling scheme, which is nearly independent of the number of spans. The fiber type has an influence on the gain

Consider the following scenario: a legacy WDM link with DP-QPSK is gradually replaced with PBSOP until there is only one legacy channel left. To model this scenario, we revert the 5-th Channel for all strategies back to a DP-QPSK signal which represents a legacy link. Other parameters remain the same. In Fig.5 we show a power sweep evaluated on the 5th channel, i.e., the legacy link. We can clearly observe a gain of up to 0.5 dB on the legacy link which we attribute to a reduction of XPM from the upgraded neighbors. Note that the gains are already reasonably high for rate 7/8 and do not increase significantly for rate 0.75.

Conclusions

We apply PBSOP as signaling technique for DML. PBSOP can be adapted flexibly to the link by trading rate against non-linear gain. On legacy DML we showed stable gains of up to 1.6dB with respect to DP-QPSK and positive effects on legacy WDM links. Furthermore, gains of about 0.5dB are possible for legacy links in a upgrade scenario.

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