On Maximum Likelihood Sequence Detectors for Single-channel Coherent Optical Communications

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Abstract *Two different detectors that account for the nonlinear signal–noise interaction in a single-channel coherent optical link are compared. The results indicate that accounting for the correlation between the samples leads to improved performance over stochastic digital backpropagation.*

Introduction

Fiber nonlinear effects is a major limiting factor in fiber-optic communication systems. An accurate channel model is necessary to optimally detect the transmitted data in the presence of nonlinear effects. However, the absence of an analytical closed-form solution of the Manakov equation, except for some specific cases, makes it hard to develop an optimal detector. Linearization of the Manakov equation is often used to find approximate analytical solutions, commonly known as perturbation-based techniques[1] (PBT). Besides these linearization techniques, the split-step Fourier method (SSFM) is often used to simulate the signal propagation in optical fibers.

Digital backpropagation[2,3] (DBP) is a technique based on the SSFM used for jointly compensating for linear and nonlinear impairments. However, two different contributions[4,5] pointed out that while DBP is able to fully compensate for nonlinear ISI (if performed for all spans), it is not the optimal strategy in the presence of signal–noise interaction. The first detector is based on the Viterbi algorithm (VA) with two different metrics, which are derived by identifying the signal statistics from a PBT. The second detector, known as stochastic DBP (SDBP)[5] and based on the SSFM, represents the uncertainty in the variables through distributions. In this paper, a direct comparison is carried out between these two detectors for the first time, considering the same scenario. By taking advantages of each of these detectors, in future work, we aim to develop optimal receivers that can be of practical use for both dispersion-managed (DM) (with inline dispersion-compensating fiber) and non-DM (NDM) links.

System Model

The system model is shown in Fig. 1, which comprises a dual-polarization transmitter, an N-span fiber-optic link with each span consisting of a standard single-mode fiber (SMF) (or a low-dispersion fiber (LDF) for DM links), a dispersion-compensating fiber (DCF) for DM links, and amplifiers. In the transmitter, a binary information sequence is mapped to a sequence of K independent and identically distributed (i.i.d.) symbols, $\mathbf{s} = (\mathbf{s}_1, \mathbf{s}_2, ..., \mathbf{s}_K)^T$, drawn from an M_c-ary constellation, which are mapped by a linear modulator. Each $\mathbf{s}_k$ is a complex length-2 vector consisting data from both polarizations. This signal is passed through the channel.

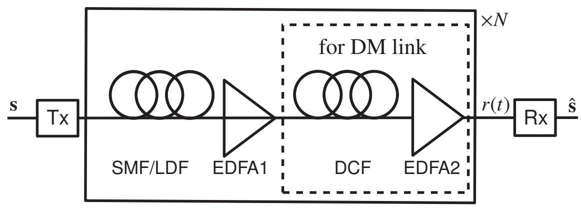

Fig. 1: System model with a fiber-optical link consisting of N spans.

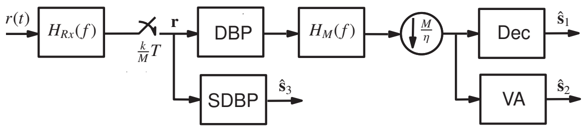

Fig. 2: Rx block of Fig. 1 consisting of a receive filter $H_{Rx}(f)$ and detection algorithms DBP, VA, SDBP.

At the receiver, coherent detection is used to convert the optical bandpass signal into an electrical lowpass signal, $r(t)$, as shown in Fig. 2. The signal, $r(t)$, is filtered with $H_{Rx}(f)$ with a bandwidth $MR/2$ and sampled at every kT/M, where T is the symbol duration, and R is the symbol rate of the system. The in-phase and quadrature components of these samples are collected in a complex vector $\mathbf{r} = (\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_{MK})^T \in \mathbb{C}^{MK}$. We assume that $\mathbf{r}$ is a sufficient statistic and an optimal detector would process this signal using a maximum a posteriori (MAP) rule: $\hat{\mathbf{s}} = \arg\max_{\mathbf{s}} p(\mathbf{s}|\mathbf{r})$, where $p(\mathbf{s}|\mathbf{r})$ is the posterior distribution of $\mathbf{s}$. With an equiprobable symbol distribution, MAP reduces to the maximum likelihood (ML) rule, and the probability distribution that determines the decision will be $p(\mathbf{r}|\mathbf{s})$. The detector that uses the ML rule is known as the ML sequence detector (MLSD). Both the detectors compared in this paper try to apply this MLSD using different tools and techniques, explained in the next section.

Detectors
The goal of the detectors under study is to apply the MLSD rule by maximizing $p(\mathbf{r}|\mathbf{s})$ with respect to $\mathbf{s}$. The received samples $\mathbf{r}$ are sent to these detectors, as shown in Fig. 2. In the first detector, based on the VA, DBP is applied followed by a filter $H_M(f)$. Then the signal is downsampled by a factor of M/η, where η is the number of samples per symbol needed for processing in the VA. In the second detector, the received samples are passed through the SDBP algorithm and decisions are taken after further processing, as will be explained in later sections. The improvements of these two detectors are compared with a detector based on DBP followed by a filter matched to the transmitter pulse shape, followed by downsampling by a factor of M, followed by a 'Dec' block. In this block, the additional phase rotation due to the average nonlinear phase noise induced by signal–noise interaction is compensated for and symbol-based decisions are made using a minimal Euclidean distance rule.

VA with Cartesian and Polar Gaussian Metric
In this detector, the VA with two different branch metrics is considered based on two different channel models. The first metric, Cartesian Gaussian (CG), is derived according to the linearized regular perturbation model. In this model, the output signal is affected by nonlinear ISI and colored Gaussian noise. Thus, conditional on the transmitted symbols $\mathbf{s}$, the in-phase and quadrature components of the output samples $\mathbf{r}$ can be modeled as correlated Gaussian variables. The second metric, polar Gaussian (PG), is based on a more accurate model[1] and obtained by accounting for the presence of nonlinear phase noise. In particular, conditional on the transmitted symbols $\mathbf{s}$, the amplitude and phase of the received samples are correlated Gaussian variables. In this detector, irrespective of what metric is used to factorize $p(\mathbf{r}|\mathbf{s})$, it was assumed that i) conditional on $\mathbf{s}$, signal samples spaced more than ν sampling times are uncorrelated and ii) conditional on the previous ν samples, the channel memory is limited to L_c symbols. It was shown[4] that ν is an important parameter to take into account the correlation between samples due to the interplay between the Kerr nonlinearity and dispersion, with a correlation time that increases with link dispersion. The MLSD rule can be implemented by a VA (with CG or a PG metric), by using a suitable training sequence in order to estimate and store in a look-up table the required conditional expectations and covariance matrices for each transition of the trellis diagram. The complexity of this detector depends on the channel memory, L_c, and on the number of correlation samples, ν. Since dual polarization is considered, two independent VA detectors, one per polarization, are employed. In this scenario, nonlinear ISI can involve a large number of symbols and thereby requires a huge number of states in the VA algorithm. For this reason, DBP is applied to reduce the nonlinear ISI followed by VA to combat the signal–noise interaction, and hence named as DBP-CG and DBP-PG depending on what metric is used.

Tab. 1: Channel parameters

	SMF	LDF	DCF
D (ps/nm/km)	16.6	4.4	–100
γ (1/W/km)	1.3	1.3	5.2
α (dB/km)	0.2	0.2	0.6

Stochastic Digital Backpropagation
In the second detector, called SDBP, $p(\mathbf{s}|\mathbf{r})$, or equivalently $p(\mathbf{r}|\mathbf{s})$ for equiprobable symbols, is obtained by doing a marginalization of the joint distribution of $\mathbf{s}$, all intermediate variables in the channel, and the received signal $\mathbf{r}$. As the fiber in the channel is simulated using the SSFM, the intermediate variables include signals after the linear and nonlinear steps of each segment of each span of the SSFM. The signals after the EDFAs in Fig. 1 are also included as intermediate variables. The main idea of SDBP is to describe these intermediate variables statistically, ending up with a description of $p(\mathbf{s}|\mathbf{r})$. This description is based on "particles" and becomes more accurate with a higher number of particle waveforms. Once $p(\mathbf{s}|\mathbf{r})$ is obtained, decisions are taken symbol-based instead of sequence-based to avoid further complexity. All these particle waveforms are passed through a filter matched to the pulse shape, followed by a symbol-rate sampler, leading to a set of particles corresponding to each transmitted symbol. To take a decision, the set of particles corresponding to a particular symbol are approximated with a bivariate Gaussian distribution and this distribution is evaluated at each of the constellation points, which leads to the symbol-based decision. These two assumptions, namely symbol-based processing and approximating a set of particles with a bivariate Gaussian distribution which make SDBP a sub-optimal detector.

Numerical Simulations
The system model of Fig. 1 is simulated to compare the detectors discussed above. For DM links, LDF is used and for NDM links, SMF is used for transmission. The noise figure for each EDFA is 5.5 dB.

The SSFM is applied with a segment length[6] of $\Delta = (\epsilon L_{\mathsf{N}} L_{\mathsf{D}}^2)^{1/3}$, where $\epsilon = 10^{-4}$, $L_{\mathsf{N}} = 1/(\gamma P)$ is the nonlinear length, $L_{\mathsf{D}} = T^2 2\pi c/(|D|\lambda^2)$ is the dispersion length, D is the dispersion parameter of the fiber, λ is the wavelength, c is the

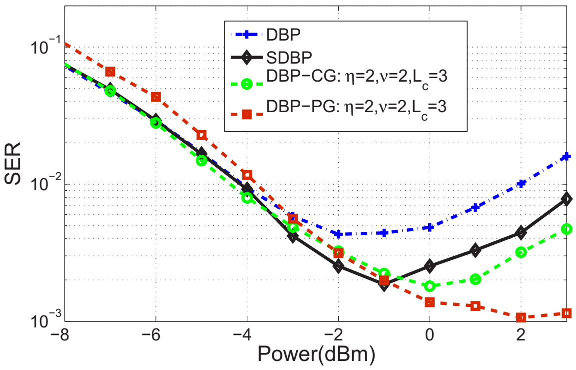

Fig. 3: 32 Gbaud DM link with QPSK modulation format with $L_{\text{LDF}} = 120$ km and $N = 25$.

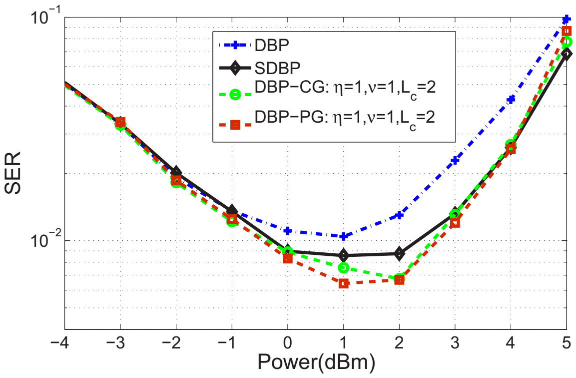

Fig. 4: 16 Gbaud NDM link with QPSK modulation format with $L_{\text{SMF}} = 120$ km and $N = 120$.

speed of light, and P is the input power to each fiber span. The number of segments per span is $M = \lceil L_x/\Delta \rceil$, where $\lceil p \rceil$ is the smallest integer not less than p, and L_x is the length of the fibers with $x \in \{\text{SMF}, \text{LDF}, \text{DCF}\}$. We used the same segment length in the backward and forward system as step size optimization (and complexity reduction) was not of concern here. The launch power into the DCF is 4 dB below that of the transmission fiber. The parameters used for SMF, LDF, and DCF are given in Table 1. The span length for the SMF and LDF is 120 km. The length of the DCF is calculated assuming a perfect inline dispersion compensation.

For SDBP, and VA for NDM links (which need $\eta = 1$), the transmit pulse shape and $H_M(t)$ are both root raised cosine. For DM links, due to the spectral broadening introduced by nonlinearites, DBP-CG and DBP-PG need $\eta = 2$ for processing and a raised cosine pulse is used at the transmitter and a rectangular filter with twice the bandwidth is used for $H_M(t)$. The receiver signal is passed through a filter $H_{Rx}(f)$, which is an ideal low-pass filter with bandwidth $MR/2$, and sampled at $M(=4)$ samples per symbol. The receiver is assumed to have perfect knowledge of the polarization state, as well as the carrier phase and the symbol timing. The number of particles used for the SDBP simulation is 500.

Fig. 3 (Fig. 4) shows the symbol error rate (SER) as a function of the input power for 32 (16) Gbaud for DM (NDM) links. We observe that SDBP, DBP-CG, and DBP-PG outperform DBP for DM links. Using detectors based on SDBP and the VA, a different optimal power is obtained and also for a given input power, lower SER is obtained. The system is more tolerant to nonlinear effects and therefore we can use higher launch power. The gains for NDM links are smaller than for DM links, as nonlinear ISI is the dominant effect and the proposed detectors, compared with DBP, account for the signal–noise interactions, which are less dominant for NDM links. It can be seen in Fig. 3 that by taking the correlation of the samples at the receiver into account, better gains are observed. In DBP-CG (DBP-PG), when $\nu = 2$ (1) and $\eta = 2$ (1), a correlation of two (one) samples spaced half (one) symbol period apart is taken into account. As can be seen from Fig. 3, SDBP, DBP-CG, and DBP-PG achieve the best performance for different input powers. Hence, no method is uniformly optimal.

Conclusions

In this initial study, we observed through simulations that the two compared detectors achieve the best performance for different input powers and no method is uniformly optimal. The VA can be improved by computing joint detection for both polarizations while SDBP can be improved by accounting for correlations among samples. The VA has exponential complexity with respect to the modulation order, whereas, the complexity for SDBP is essentially independent of the modulation format used, and results for SDBP using 16-QAM were presented in an earlier work[5]. This study suggests that the correlation of the samples is an important aspect when accounting for the nonlinear signal–noise interactions. As reported in earlier works, the improvement over DBP is very small for NDM links.

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