Post-detection nonlinear distortion for efficient MLSD in optical links

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Abstract: In this paper, we investigate the use of nonlinear distortion of the electrical post-detection signal in order to design simple, yet very effective, maximum likelihood sequence detection (MLSD) receivers for optical communications with direct photo-detection. This distortion enables the use of standard Euclidean branch metrics in the Viterbi algorithm which implements MLSD. Our results suggest that the nonlinear characteristic can be optimized with respect to the uncompensated chromatic dispersion and other relevant system parameters, such as the extinction ratio. The proposed schemes with optimized distortion exhibit the same performance of more sophisticated MLSD schemes, still guaranteeing more efficient Viterbi algorithm implementation.

OCIS codes: (060.4510) Optical communications.

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1. Introduction

Electronic signal processing, in particular maximum likelihood sequence detection (MLSD), is gaining increasing importance in optical communications [1, 2]. MLSD can deal with almost any impairment affecting the optical communication channel: chromatic dispersion (CD), polarization mode dispersion (PMD), and fiber nonlinearity, to name a few [3]. MLSD is a well-known and established technique [4, 5] and several "off-the-shelf" MLSD practical implementations are based on the Viterbi algorithm (VA) [6] and rely on the concept of *metrics*. In particular, standard VAs for additive white Gaussian noise (AWGN) channels take advantage of the use of *Euclidean* metrics [4, 5], based on the concept of minimum distance in the signal space.

Several works address the metric computation issue in MLSD for optical communications [1, 7, 8]. Particular attention is given to the metric computation and its accurate approximations. In [1], (i) a near-optimal metric based on the results in [9], (ii) a generic histogram-based metric, and (iii) a Gaussian metric for theoretical bit error rate (BER) analysis purposes are considered. In [7], exact metric evaluation techniques, based on the results in [10], as well as an accurate approximation, are proposed and used for system performance analysis. In [11], it is shown that the square-root of the received signal can be statistically approximated as the output of an Additive White Gaussian Noise (AWGN) channel. This approximation assumes (i) high Optical Signal-to-Noise Ratio (OSNR) and (ii) a low extinction ratio at the transmitter (i.e., lower than 10 dB). Both conditions are not satisfied in many practical scenarios. In [12], the authors propose the use of a square root block, placed *between* the photo-detector and the post-detection filter, to combat the nonlinearity introduced by the square-law photo-detector and to improve the performance obtained with a linear equalizer. We remark that the use of Gaussian approximations for the statistical description of the received signal is a subject which received significant attention in the past for the purpose of BER-based performance analysis of optical communication systems (see, e.g., [13, 14, 15, 16]).

In this paper, we propose the introduction and optimization of a simple nonlinear processing block *after* the post-detection filter at the receiver. The goal of this non-linear block is to modify the statistics of the observed sample sequence in order to enable the use of simple Euclidean metrics in the VA and, therefore, the implementation of low-power, low-cost and high-speed Viterbi processors. We adopt a simple single-parameter non-linear block model. We present MLSD performance results and show that the use of a proper nonlinear characteristic allows a practically optimal performance at any values of the extinction ratio and channel conditions. With the use of Euclidean metrics, the memory requirements for the metric look-up table, usually adopted for metric computation in high speed VA implementations, is significantly reduced.

2. Nonlinear processing and metrics

MLSD chooses the most likely data sequence given an observed sequence of samples. In other words, it chooses the data sequence $\hat{\mathbf{a}}$ such that

$$\hat{\mathbf{a}} = \underset{\mathbf{a}}{\operatorname{argmax}} \log p(\mathbf{r}|\mathbf{a}) \tag{1}$$

where $p(\mathbf{r}|\mathbf{a})$ is the probability density function (PDF) of the observable vector $\mathbf{r}$ given the data sequence $\mathbf{a}$. The VA efficiently carries out MLSD by decomposing the data sequence likelihood

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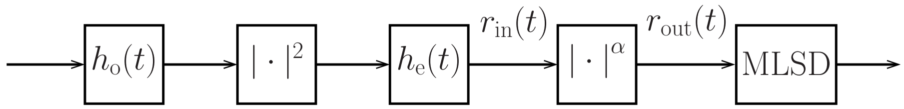

Fig. 1. Scheme of a receiver front-end with the proposed nonlinear processing block after the postdetection filter.

into a sum of *metrics*, namely simple terms which depend on a limited portion of the data sequence [6]. This corresponds to the following decomposition of the logarithm of the PDF in (1):

$$\log p(\mathbf{r}|\mathbf{a}) \simeq \sum_i \log p(r_i|\mathbf{a}) \tag{2}$$

where the sum is carried out over all observables in the sequence, $p(r_i|\mathbf{a})$ is the PDF of the i-th observable given the data sequence $\mathbf{a}$, $\log p(r_i|\mathbf{a})$ is the *metric* and the *approximation* is due to the assumption of conditional independence of the observables. In general, for each observable, a set of metrics are computed as functions of the data sequence. In the AWGN case, a metric corresponds to the square of the Euclidean distance between the received sample and a hypothetical value that would have been received in the absence of noise for each data sequence [5]. This guarantees minimal complexity in the metric computation and enables the use of a consolidated set of algorithms for telecommunications. We remark that Euclidean metrics arise when the conditional PDFs of the observables are Gaussian and *their variance does not depend on the data sequence*.

The statistical distribution of the noise affecting the electrical signal at the receiver side in an optical transmission system *is not* Gaussian [11]. This causes important changes in the structure of MLSD devices, since it does not allow the application of standard techniques for AWGN channels [4] based on Euclidean metrics.

In Fig. 1, the structure of a a receiver with nonlinear processing of the electrical post-detection signal is shown. The receiver comprises an optical filter with impulse response $h_o(t)$, a square-law photo-detector, a post-detection electrical filter with impulse response $h_e(t)$, and a memoryless nonlinear block whose input/output characteristic is

$$r_{out}(t) = |r_{in}(t)|^\alpha \tag{3}$$

where $r_{in}(t)$ is the output of the post-detection electrical filter at epoch t, $r_{out}(t)$ is the output of the nonlinear processing block, and $\alpha \in (0,1]$.

3. Performance analysis

In the following, we consider two 10 Gb/s optical communication systems with direct photo-detection based on: (i) optical duobinary modulation (ODBM) and (ii) on-off keying (OOK) with non-return-to-zero (NRZ) pulses. The ODBM scheme employs a 5-th order Bessel modulation filter with 3 GHz bandwidth, a 3-rd order Bessel optical front-end filter with bandwidth 33 GHz, and a 5-th order Bessel post-detection filter with 7.7 GHz bandwidth. The OOK scheme, employs a modulator with an extinction ratio of 23 dB, a 3-rd order Bessel modulation filter with bandwidth 9.5 GHz, a 3-rd order Bessel optical front-end filter with bandwidth 32.5 GHz, and a 5-th order Bessel post-detection filter with bandwidth 7 GHz. The OSNR is defined as the ratio between the average received optical power and the noise power in a bandwidth of 0.5 nm at 1550 nm carrier wavelength. In the BER analysis, the impact of uncompensated CD will be taken into account.

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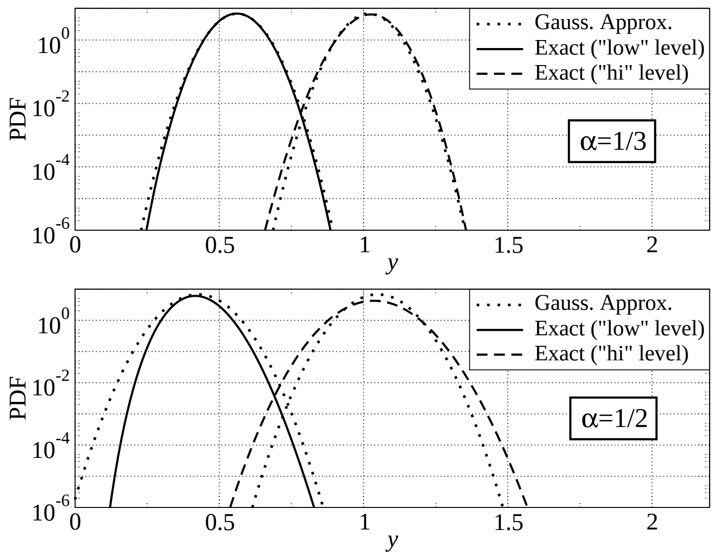

Fig. 2. Comparison between exact PDFs and Gaussian approximations (Euclidean metrics). Two data sequences, corresponding to high (all "0" pattern) and low (all "1" pattern) levels, and two values of α, namely $1/2$ and $1/3$, are considered.

3.1. Qualitative metric analysis

In Fig. 2, a comparison between the exact PDF of a sample of the observed signal after nonlinear distortion and a Gaussian approximation is shown for the considered ODBM system, in the absence of CD. The OSNR is equal to 5 dB. Two sequences corresponding to all-0 and all-1 patterns (*on* and *off* states, respectively) and two values of α ($1/2$ and $1/3$, respectively) are considered. The two Gaussian approximations are chosen with means equal to the corresponding exact means and identical variance, thus enabling the use of Euclidean metrics. Even if in Fig. 2 the variance is chosen to minimize the mean square error between exact an approximated PDFs, we remark that VAs based on Euclidean metrics are insensitive to the value of the PDF variance [4]. Note that, more accurate Gaussian approximations of the PDFs could be derived using a different variance for each data sequence. However these approximations do not allow immediate use of Euclidean metrics.

Figure 2 qualitatively shows that, in order to obtain approximate Euclidean metrics, it is important to optimize the value of the α coefficient. In order to optimize this exponent, one can observe that the conditional PDFs of the observables at the output of AWGN channels have maximum values and variances independent of the data sequence. One could optimize α by making the actual PDFs maxima meet as close as possible this condition. The maxima of the PDFs can be evaluated by statistical analysis on the observables and used to adjust α in a feedback fashion. Since the PDF maximum is in correspondence with the most likely outcome for the observable, it is arguable that optimization algorithms based on PDFs maxima evaluation will be fast, due to the availability of relevant observables.

We remark that our approach does not account for phase noise in the transmitted optical signal. Phase noise can be dealt with using the analytical approach in [14, 15], although this would require further investigation to preserve the use of Euclidean metrics.

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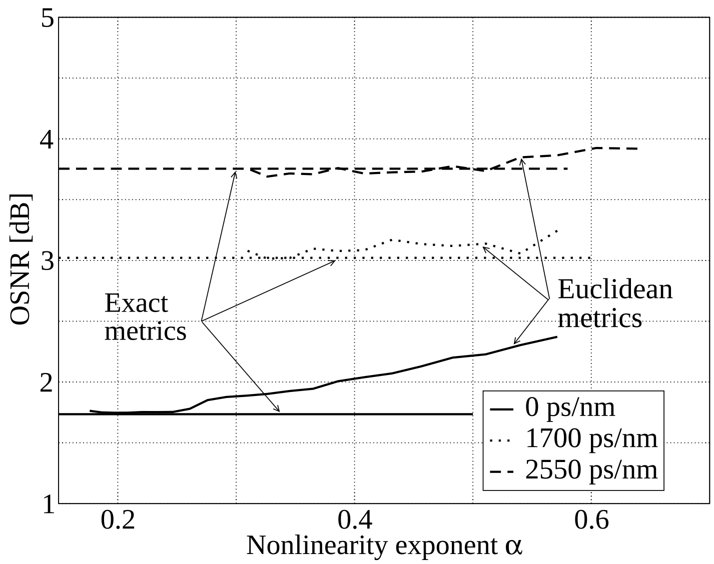

Fig. 3. OSNR, as a function of the nonlinearity exponent α, at a BER equal to 10^{-3}. CD values equal to 0 ps/nm, 1700 ps/nm, and 2550 ps/nm are considered. For comparison, the performance of the receiver with accurate branch metrics is also shown (horizontal lines).

3.2. Optimization of the nonlinearity exponent

In order to better understand the benefits brought by nonlinear processing of the post-detection signal, we analyze the performance of the considered OOK scheme as a function of the parameter α in (3). The receiver comprises a 16-state VA block with Euclidean branch metrics and sampling rate of 2 samples per bit interval. As a reference, an equivalent MLSD receiver, using the accurate metrics derived from the results in [10], will also be considered. As common practice, conditional independence of the observables is assumed in all cases [1, 11].

In Fig. 3, the OSNR required to achieve a BER equal to 10^{-3} is shown as a function of the nonlinearity exponent α. Various values of the uncompensated CD, namely 0 ps/nm, 1700 ps/nm and 2550 ps/nm, are considered. Clearly, the optimal value of α depends on the CD, especially at medium-low dispersion values. The horizontal lines represent the OSNR needed by the MLSD algorithm using the accurate metrics in [10]. The optimization of the nonlinear exponent seems a simple solution to practically achieve close-to-optimal performance.

3.3. OSNR performance with optimized nonlinearity exponent

In the following, we perform a comparative analysis of the considered OOK scheme with 16-state MLSD, with various values of α, and an MLSD OOK scheme using the accurate metrics derived from [10]. In Fig. 4, the OSNR required to achieve a BER equal to 10^{-3} is shown as a function of the CD. The performance of the Euclidean metric-based MLSD receivers with $\alpha = 1/2$, $\alpha = 1/3$, and optimized α is shown. The optimized curve is obtained by optimizing the parameter α for every CD value. As one can see, the simplified MLSD receiver with nonlinear distortion guarantees a performance basically equal to that of the MLSD receiver with accurate branch metrics. As one can observe from the results in Fig. 4:

- for dispersion values lower than 1000 ps/nm, the performance of the simplified MLSD receiver with optimized α and $\alpha = 1/3$ is better than that of the simplified MLSD receiver with $\alpha = 1/2$—for instance, the OSNR gain in B2B is approximately 0.5 dB;

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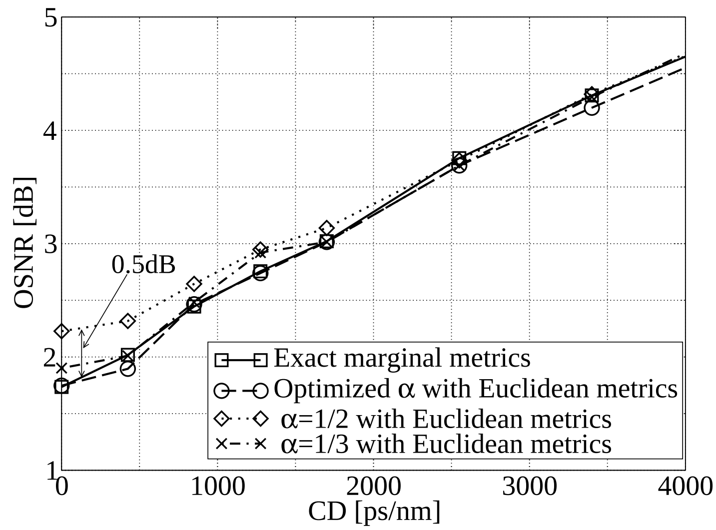

Fig. 4. OSNR, as a function of the CD, at BER equal to 10^{-3}. The behavior of the OSNR is analyzed for $\alpha = 1/2$, $\alpha = 1/3$, and optimized value of α. For comparison, the OSNR required by a VA with accurate metrics is also shown.

- for dispersion values higher than 1000 ps/nm, the performance of the simplified MLSD receiver with optimized α and $\alpha = 1/3$ is only slightly better than that of the simplified MLSD receiver with $\alpha = 1/2$.

Moreover, one can observe that there are CD regions where the optimized nonlinear distortion scheme performs slightly better than the one with accurate branch metrics. This should be attributed to two sources of sub-optimality in the system with accurate branch metrics. First, the accurate branch metrics do not completely represent the statistical distribution of the observables, which are not independent conditionally on the data sequence [7]. Second, at high CD values, 16 states are not sufficient to represent the memory of the transmission scheme with high accuracy.

4. Concluding remarks

In this paper, we have investigated the performance of a simplified MLSD receiver based on nonlinear distortion of the post-detection signal with law $|\cdot|^{\alpha}$, $\alpha \in (0,1]$, followed by a VA block with Euclidean metrics. We have considered optimization of the exponent α of the nonlinear distortion law: our results show that for all considered CD values, an MLSD receiver using Euclidean metrics together with optimized nonlinear distortion has the same performance of a receiver using accurate branch metrics derived from [10]. The most important implication of our results is that the proposed optimized post-detection nonlinear distortion makes it possible to effectively use "standard" VAs (i.e., with Euclidean minimum-distance branch metrics) in MLSD for optical communications. This implies a size reduction of the metric look-up table by a factor $\gamma = 2^{\eta N_s}$, where N_s is the number of bits per sample and η is the number of samples per bit interval. In typical applications, N_s is 3 to 5 bits and η is 2 samples per bit interval, yielding a reduction factor γ from 32 to 1024. The metric look-up table size is proportional to the number of states of the VA, which is increasing exponentially in current applications. Therefore, the use of the proposed scheme is likely to significantly reduce both hardware requirements and power consumption in application-specific integrated circuits (ASIC) implementations. Moreover, Euclidean metrics enable, through the use of standard algorithms, simplified and fast channel acquisition, which may be crucial for future applications.

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