A Transition Metric in Polar Co-ordinates for MLSE of a Complex Modulated DML

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Abstract: We propose a metric for MLSE-Viterbi differential decoding of complex modulation of directly modulated lasers (CM-DML) that reports SNR gains of 1.8 dB at BER=10^{-3} on a simulated PAM4 signal with a typical linewidth enhancement factor $\alpha = 4$

OCIS codes: (060.1660) Coherent communications, (060.4510) Optical communications, (060.4080) Modulation.

1. Introduction

Coherent detection is continuously gaining ground in shorter-range optical communications, while the research community tries to innovate with cost-sensitive solutions to keep up with the market demands, which become tighter as the range of application approaches the user end. In this context, an emerging trend is the combination of directly modulated lasers (DML) and coherent receivers. In [1] it was shown that the frequency chirp of the DML, historically considered an impairment, can be beneficial if the signal is coherently detected at the receiver, since both the observed amplitude and phase convey useful information. Later, in [2], the authors reported, by means of simulation and experimental verification, that using the Viterbi algorithm for sequence decoding results in a significant gain in SNR (up to 10 dB) with respect to the conventional IMDD approach, where a simple PAM4 signal had been used to directly modulate a DFB laser. This technique is conventionally referred to as *complex modulation* of DML, or CM-DML.

2. Background

2.1. DML-induced chirp model review

The frequency chirp of a laser is the change on its optical frequency induced by a change on its driving current. In a complex-baseband representation, where the optical angular centre frequency ω_c is zero and T is the symbol period, the phase jump measured between two consecutive samples, at times $t-T$ and t, is the combination of three terms, as

$$\Delta\varphi(t) = \frac{\alpha}{2}\left(\log\frac{P(t)}{P(t-T)} + \int_{t-T}^{t} \kappa P(t)\,dt\right) + \varphi_{pn}(t), \tag{1}$$

where the two terms in brackets are the transient and adiabatic chirp, being κ the coefficient of the latter, α is the linewidth enhancement factor, and $\varphi_{pn}(t)$ is Gaussian phase noise with zero mean and variance

$$\sigma_p^2 = 2\pi\Delta\nu T, \tag{2}$$

where $\Delta\nu$ is the combined linewidth of the transmitter and local oscillator (LO) lasers in Hz. Both the adiabatic chirp and the phase noise are mechanisms that introduce memory in the channel, posing a complexity problem for maximum-likelihood sequence estimation (MLSE) algorithms.

2.2. The previously proposed algorithm

In [2] the authors used a differential approach on the received signal in order to suppress the phase noise-induced channel memory, enabling the execution of a reduced-complexity version of the MLSE-Viterbi algorithm, having a sequence length of 2 symbols only. The detailed description of its implementation is given in Table 1 in [2]. The transition distance, $\lambda(\chi_t)$, (Eq. (5) in [2]) is given by

$$\lambda(\chi_t) = |P(t-T) - x(t-T)| + \left|\sqrt{P(t)}\cdot\exp(j\Delta\varphi(t)) - \sqrt{x(t)}\cdot\exp(j\Delta\varphi_E(t))\right| \tag{3}$$

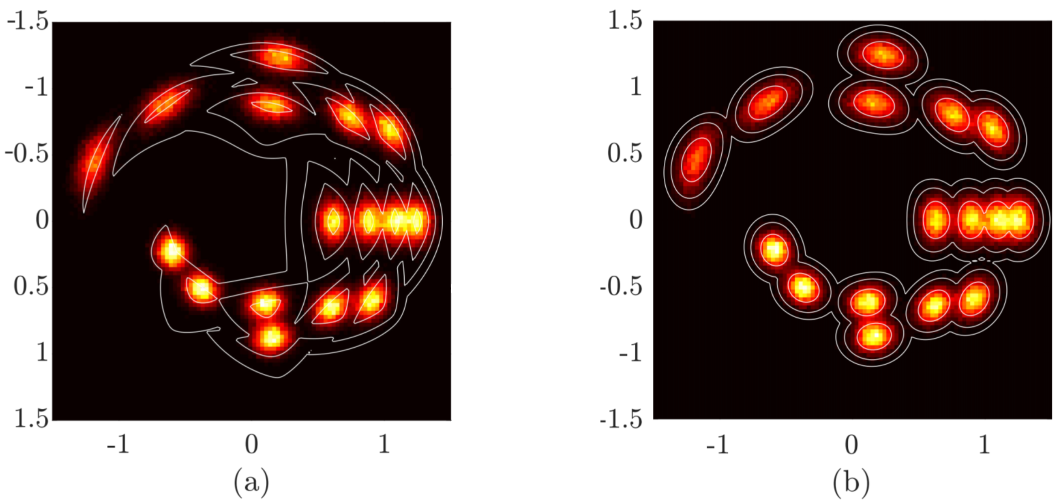

Fig. 1. Density map of differentially detected PAM4 signals using a DML ($\alpha = 4$, SNR = 15 dB). On top of it, the equidistant curves computed with the Original (a) and Proposed (b) metrics.

where $\Delta\varphi_E(t)$ is the predefined transition phase jump obtained with a simplified version of Eq. (1) given by

$$\Delta\varphi_E(t) = c_1 \log \frac{x(t)}{x(t-T)} + c_2 (x(t-T) + x(t)), \tag{4}$$

where $x(t)$ is the power of the transmitted symbol at time t, and the coefficients $c_1 = \alpha/2$ and $c_2 = \kappa\alpha T/4$.

To see how the metric in Eq. (3) —hereinafter referred to as the Original— approximates the probability density of observed transitions, Fig. 1 (a) shows its generated contour of equidistant curves plotted over the probability density map of a differentially detected DML-PAM4 signal with $\alpha = 4$ and SNR arbitrarily set to 15 dB (κ and $\Delta\nu$ are neglected, the y-axis conveniently inverted).

3. The proposed transition distance in polar coordinates

Inspired by a recent publication [3], where the partially coherent AWGN channel is approximated in polar coordinates, herein we propose an alternative version that considers the differential phase error as the contribution of three zero-mean, normally-distributed terms: the phase noise with variance σ_p^2, and the AWGN-induced angular deviation of each of the two symbols involved in the transition, which, in an *a posteriori* manner, depends on the transmitted and observed intensities as follows [4]

$$\sigma_n^2(t) \approx \frac{N_0}{2\sqrt{P(t)x(t)}} \tag{5}$$

where the AWGN power N_0 is computed from the SNR in dB as $10\log_{10}(P_{sig}/N_0)$, with P_{sig} as the average transmitted power, and the differential phase noise variance is obtained as in Eq. (2).

Therefore, the Proposed —as it will be referred to— transition distance $\lambda_P(\chi_t)$ can be obtained in polar co-ordinates as the sum of both modulus and (differential) angular squared distances, that is

$$\lambda_P(\chi_t) = \left|\sqrt{P(t)} - \sqrt{x(t)}\right|^2 + \frac{|\Delta\varphi(t) - \Delta\varphi_E(t)|^2}{\sigma_n^2(t-T) + \eta + \sigma_n^2(t)} \tag{6}$$

where η is the so-called rotation factor equal to $2N_0/\sigma_p^2$.

To visually understand the difference between the two metrics, the contour of equidistant curves for the Proposed are also included in Fig. 1 (b), for the same simulation parameters as in (a). It is clear that, while the Original metric shows irregular equidistant curves, the Proposed one exhibits an almost perfect match with the underlying density plot.

4. Simulation results

The simulation in [2] is reproduced here for a fair comparison. The transmitted signal is a chirped PAM4 with three tested values of α: 2, 4, and 6, while c_2 is kept at 0.5. For the phase noise, $\Delta\nu = 10$ MHz is used and the symbol rate

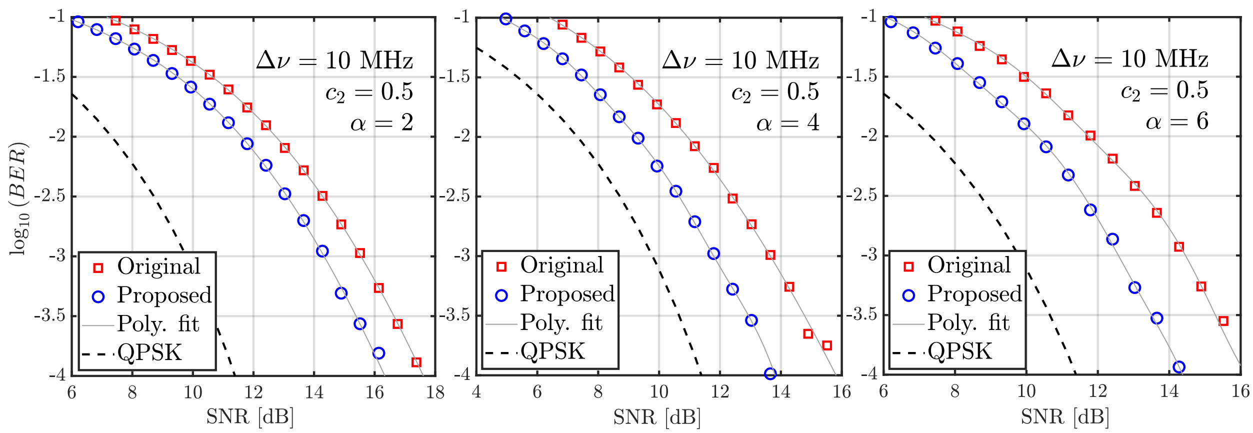

Fig. 2. Top: BER versus SNR obtained with the 2-tap Viterbi algorithm (VA) using the Original metric (square markers) and the Proposed metric (circle markers) in a simulated PAM4 CM-DML system with adiabatic chirp coefficient $c_2 = 0.5$, combined linewidth $\Delta\nu = 10$ MHz, a symbol rate of 12.5 GBaud, and α being 2 (left), 4 (center), and 6 (right). A polynomial fit of the results (solid line) and the theoretical BER curve for QPSK (dotted line) are shown for reference.

is 12.5 GBd. Figure 2 shows the computed (pre-FEC) BER after decoding with the VA algorithm proposed therein. The curves, labeled as "Original" and "Proposed", correspond to the cases where Eqs. (3), or (6) are used to compute each transition distance, respectively. In order to quantify the benefit of the proposed algorithm over that previously published we consider the SNR gains for a target BER of 10^{-3}. For the case of $\alpha = 2$ the SNR benefit of the proposed algorithm at BER=10^{-3} is 1.2 dB. On increasing the value of α to 4 the SNR gain increases to 1.8 dB at a BER=10^{-3}. When α is increased to 6 the same 1.8 dB is also obtained for a BER of 10^{-3}. Given that $\alpha = 4$ is a representative value for current commercially available directly modulated lasers [1], the results indicate that for 25 Gbit/s using 12.5 GBd PAM4, the required SNR would be 11.9 dB using the proposed metric. While the performance is 2.1 dB worse than the ideal QPSK case, given traditional PAM4 requires an SNR of 17.1 dB [5], the gain of using coherent detection is 5.2 dB. This gain makes this an attractive proposition for applications such as the ONU transmitter in access networks.

5. Conclusions

This paper deals with the problem of complex modulation of DMLs, focusing on a previously published technique based on differential detection and a reduced-complexity version of the Viterbi algorithm. We have introduced an alternative form in polar co-ordinates to compute the transition distance that, through numerical simulations, exhibit a SNR gain of 1.8 dB at a BER=10^{-3} for a typical linewidth enhancement factor $\alpha = 4$.

6. Acknowledgement

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