AN EFFICIENT NON LINEAR RECEIVER FOR HIGH DENSITY OPTICAL RECORDING

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ABSTRACT

This paper presents an innovative Non Linear Receiver (NLR) for the high density optical channel. This receiver is based on the combination of Maximum Likelihood Sequence Estimation (MLSE) and nonlinear Inter-Symbol Interference (ISI) cancellation. For the nonlinear channel description a suitable model based on the Volterra series has been adopted. Simulation results show that the proposed NLR performs better than traditional equalizers introduced for nonlinear channels, such as Nonlinear Adaptive Volterra Equalizer (NAVE) and Nonlinear Decision Feedback Equalizer (NDFE), and it offers significant advantages with respect to traditional MLSE.

1 INTRODUCTION

The information density on optical discs can be augmented either increasing the operating spatial frequency or decreasing the track pitch (i.e., the distance between adjacent tracks). In high density systems the read-out signal is significantly affected by Inter Symbol Interference (ISI) and cross talk (XT) among adjacent tracks.

In [1] we considered various equalization algorithms, assuming a linear model for the optical channel. In case of high density recording, however, the linear model based on the Modulation Transfer Function (MTF) is not realistic, and also nonlinear terms must be included [2].

A model close to the read-out process was developed by Hopkins [3] using the optical scalar theory. Using the same approach, in [4] an optical physical model has been implemented. This model has then been used to identify a nonlinear analytical model based on the Volterra series [4].

In this work the problem of nonlinear channel equalization is addressed. In particular, we present an innovative Non Linear Receiver (NLR) architecture studied for the nonlinear optical channel. Its performance is compared with that of Nonlinear Adaptive Volterra Equalizer (NAVE) [5], Nonlinear Decision Feedback Equalizer (NDFE) [6] and traditional MLSE [7] for linear channels. The proposed NLR shows significant performance improvement with respect to all other algorithms, expecially as the density increases.

The paper is organized as follows. In Section 2 the nonlinear channel model is presented. Section 3 is devoted to the description of the proposed NLR, whereas simulation results are discussed in Section 4. Concluding remarks are given in the final section.

2 THE OPTICAL DISC MODEL

Hopkins's analysis [3] is shortly described as follows. From the laser source the light propagates, through the lens, towards the disc surface. The scalar theory describes mathematically the field propagation as a Fourier transform of the scalar input field. The disc reflectivity is modeled making use of the Fourier series analysis for periodic structures. The reflected light is equal to the phase profile of the disc, times the incident field. The photodiode signal is the electro-optical conversion of the reflected field after back-propagation to the detector, i.e. after another Fourier transform.

The general results of the analysis carried out through the physical model, show that a linear model for the optical system is not an accurate approximation for high density optical discs [4].

2.1 The Volterra Model

To characterize the nonlinear behaviour of the high density optical disc, a mathematical model based on a Volterra series was considered [4].

According to the scalar theory the propagation of light can be represented as a chain of linear transformations, followed by the quadratic distortion generated by the photodetection process. Hence, a second order Volterra model leads to an accurate analytical description of the read-out process.

The nonlinear optical channel is completely characterized by its Volterra kernels, so an appropriate kernel identification procedure was developed in previous works [4]. The output signals obtained from the optical model and from the Volterra series coincide, as expected. Simulations have shown that, even at the Compact Disc Digital Audio (CDDA) density, the contributions of second order terms are not negligible, and that nonlinear ISI becomes worse as the information density is increased [4].

3 THE PROPOSED NON LINEAR RECEIVER

Reliable recovery of the information stored on the disc requires appropriate equalization techniques, to get rid of both linear and nonlinear ISI. First, we studied the performance of traditional receivers for linear channels based on symbol by symbol decision, like minimum Mean Square Error equalization (MSE) and Decision Feedback Equalization (DFE). Then, we analyzed Maximum Likelihood Sequence Estimation (MLSE) [7].

MLSE is the optimum receiver for linear channels, since it bases the decision on the entire transmitted sequence. An analysis of MSE, DFE and MLSE in presence of a *linear* channel is reported in [1]. As long as the channel is linear, MLSE outperforms MSE and DFE. We have found, however, that MLSE shows a significant performance loss due to nonlinearity, if the channel is more realistically described by the second order Volterra model [9]. In this situation, equalizers specifically studied for nonlinear channels, like Nonlinear Adaptive Volterra Equalizer (NAVE) [5] and Nonlinear Decision Feedback Equalizer (NDFE) [6], achieve performance close to MLSE, with lower complexity [9]. Then, they should be preferred to MLSE. Nevertheless, they are not the optimal solution at high information densities, because they are based on a symbol by symbol approach [9].

On the other hand, the optimum sequence estimator for nonlinear channels [8] requires a bank of M^L matched filters (where M is the cardinality of the symbol alphabet and L is the channel memory), followed by a modified Viterbi algorithm with metrics taking care of both linear and nonlinear terms. The complexity of this receiver is very high. These considerations have triggered the idea of an innovative Non Linear Receiver (NLR) described in the following subsections.

3.1 Metrics computation for the nonlinear optical channel

As previously mentioned, Maximum Likelihood Sequence Estimation (MLSE), which is based on the entire transmitted sequence, is the optimum reception technique also in the case of nonlinear channels. However, its computational complexity is too high. If M is the cardinality of the symbol alphabet and L is the channel memory, the maximum likelihood receiver, in fact, requires a bank of M^L matched filters (MF), followed by a Viterbi detector (VD), which makes use of modified metrics, according to the presence of non-linearity [8]. Fortunately, strong semplifications are possible in the case of the optical channel.

If $r(t)$ denotes the received signal, $n(t)$ the Additive White Gaussian Noise (AWGN) and $y(t)$ the nonlinear optical channel output, the received signal $r(t)$ can be expressed as

$$r(t) = y(t) + n(t) \tag{1}$$

The signal $y(t)$, which can be derived from Volterra kernels, neglecting the zeroth order kernel h_0 can be rewritten in the form

$$y(t) = y_1(t) + y_2(t) \tag{2}$$

where $y_1(t)$ is the first order kernel response and $y_2(t)$ is the second order kernel response, i.e. the non-linear contribution to the channel output.

Maximum likelikood sequence estimation requires that the likelihood function λ be maximized with respect to all possible transmitted sequences. In presence of AWGN, λ can be expressed as follows:

$$\lambda = \frac{2}{N_0}\int y(t)r(t)dt - \frac{1}{N_0}\int y^2(t)dt \tag{3}$$

Substituting Eqs. 1 and 2 in Eq. 3 we obtain the form of the likelihood function in the case of the non-linear optical channel [9], described by a second order Volterra kernel, namely

$$\begin{aligned}\lambda = \frac{2}{N_0}\int y_1(t)r(t)dt + \frac{2}{N_0}\int y_2(t)r(t)dt \\ -\frac{1}{N_0}\int y_1^2(t)dt - \frac{1}{N_0}\int y_2^2(t)dt \\ -\frac{2}{N_0}\int y_1(t)y_2(t)dt.\end{aligned} \tag{4}$$

Let us denote the five terms in Eq. 4 by α_1, α_2, β_1, β_2, β_{12} respectively, i.e.,

$$\lambda = \alpha_1 + \alpha_2 + \beta_1 + \beta_2 + \beta_{12}. \tag{5}$$

The terms α_1 and β_1 in Eq. 5 are the same that would be required in the case of a linear channel, i.e., the cross-correlation between the received signal and the channel impulse response, and the energy of the channel impulse response [7]. The terms α_2, β_2 and β_{12} in Eq. 5, on the other hand, represent additional contributions due to non-linearity. The term β_2, namely the energy of the second order distortion, is a fourth order contribution that can be neglected. The third order term β_{12} is close to zero (on average) because the first and second order outputs $y_1(t)$ and $y_2(t)$ turn out to be uncorrelated [9]. Then, the only relevant nonlinear term in Eq. 5 is α_2, which takes into account the presence of nonlinear ISI. Hence, if we can remove nonlinear ISI before maximum likelihood sequence estimation, with appropriate equalization structures such as Volterra equalizers, the metrics for the nonlinear optical channel is the same as that for linear channels.

3.2 The Non-Linear Receiver

To realize an adaptive Maximum Likelihood Sequence Estimator, in the case of linear channels, we can make use of the combination of an adaptive Matched Filter (MF) and a cascaded Viterbi Detector (VD), as shown in [7]. To extend the MLSE structure to the non-linear optical channel, we may add a Non-Linear Canceller (NLC), for nonlinear ISI suppression, to the adaptive MF. Then, the VD can make use of the ordinary expressions for metrics computation. The combination of the NLC, the adaptive MF and the VD leads to the proposed Non-Linear Receiver (NLR).

The adaptive MF can be easily implemented by means of a transversal Finite Impulse Response (FIR) filter with N taps g_i, whose output z_n at the n-th iteration is expressed by

$$z_n = \sum_{i=1}^{N} g_i r_i \tag{6}$$

where r_i are the samples of $r(t)$ spaced by T seconds (T is the channel bit duration). Using the steepest descent algorithm, the filter taps can be adaptively updated according to the equations [7]

$$g_i^{(n+1)} = g_i^{(n)} - \theta e_n r_i^{(n)}, \qquad 1 \le i \le N \tag{7}$$

$$\hat{s_l}^{(n+1)} = \hat{s_l}^{(n)} + \phi(e_n \hat{a}_{n-l} + e_n \hat{a}_{n+l}), \qquad 1 \le l \le M \tag{8}$$

where $\hat{s_l}$, $|l| \le M$, are the M samples of the estimated auto-correlation of the linear part of the channel response, $\hat{a}_n$ is the estimate of the transmitted bit a_n, θ and ϕ are the updating steps, and e_n is the signal error defined as follows

$$e_n = z_n - \sum_{l=-M}^{+M} \hat{s}_l \hat{a}_{n-l} \tag{9}$$

For nonlinear ISI suppression, the samples r_i should be processed by a nonlinear combiner, whose outputs are all possible products of couples of samples $r_h r_k$, $1 \le h \le N$, $1 \le k \le N$. If N is the number of linear taps of the adaptive MF, the combiner generates N^2 products u_i. Each combiner output is used as an input of a transversal FIR filter with N^2 taps w_i. The filter operates as an NLC, and its ouput c_n, at the n-th iteration, is given by

$$c_n = \sum_{i=1}^{N^2} w_i u_i \tag{10}$$

Using again the steepest descent algorithm for updating the NLC coefficients we get

$$w_i^{(n+1)} = w_i^{(n)} - \delta \tilde{e}_n u_i^{(n)}, \qquad 1 \le i \le N^2. \tag{11}$$

where δ is the algorithm updating step, and $\tilde{e}_n$ is the signal error derived with the estimation delay D:

$$\tilde{e}_n = c_n - \hat{a}_{n-D}. \tag{12}$$

The NLC and the MF form a preliminary equalizer whose output h_n is given by

$$h_n = c_n + z_n \tag{13}$$

Then, the signal h_n is only affected by linear distortion, and it can be processed by a VD the usual way.

4 SIMULATION RESULTS

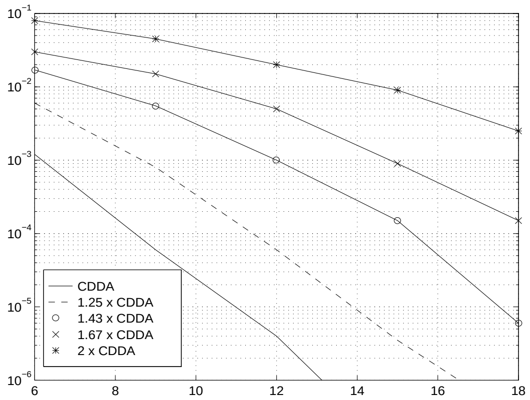

Figure 1: Performance of NLR versus E/N_0, for various information densities

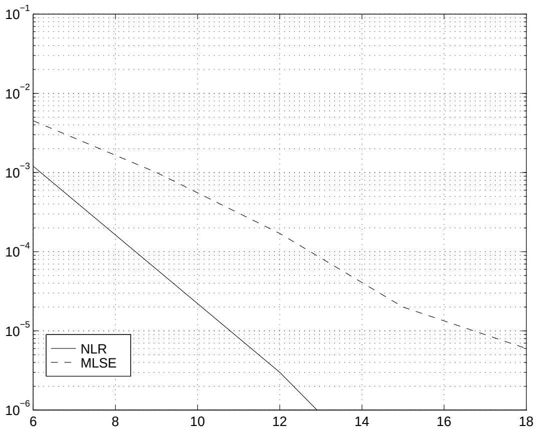

Figure 2: Performance comparison of NLR and MLSE at the CDDA density

Simulations have been carried out assuming the optical parameters of the Compact Disc Digital Audio (CDDA) system as a reference: the numerical aperture of the objective $NA = 0.45$, the laser wavelength $\lambda = 0.780 \mu m$, and the tangential velocity $v = 1.25 m/s$.

The definition of the energy per information bit may be ambiguous, due to nonlinear terms. Hence, we adopt the following notation. Let us denote the peak to peak steady state response (to a long sequence of pits and lands, respectively) as V_{pp}. Then, if T is the bit duration, a signal energy measure is expressed by the quantity $E = T(V_{pp}/2)^2$. We evaluated the bit error rate (BER) as a function of the signal-to-noise ratio E/N_0, where N_0 is the one-sided power spectral density of additive Gaussian noise.

Simulations have been carried out with different information densities, obtained increasing the spatial frequency (for instance, in the following 1.25 x CDDA means that the spatial density is 1.25 times the CDDA density).

Fig. 1 shows the NLR performance versus E/N_0, for different information densities, ranging from the CDDA density to twice as much. Fig. 2 shows a comparison beetween NLR and MLSE, at the CDDA density. Even with little nonlinear ISI, NLR offers a significant improvement with respect to MLSE, which is the optimum receiver for a linear channel. The performance improvement is even more impressive at higher information densities [9].

Fig. 3 shows that NLR performs significantly better than symbol by symbol equalizers introduced for nonlinear channels, namely NAVE and NDFE, at the CDDA density. Similar considerations hold for higher information densities [9].

A further performance comparison has been carried out between the NLR, applied to the nonlinear channel, and the MLSE applied to the linear part only of the channel, i.e. neglecting the second order Volterra kernel. Assuming the BER value of 10^{-3} as a reference, the performance comparison has shown that NLR suffers from a performance degradation, with respect to MLSE, of only 0.2 dB, 0.3 dB, 0.5 dB, and 0.6 dB respectively at the densities CDDA, 1.25 x CDDA, 1.43 x CDDA, and 1.67 x CDDA. Since MLSE is the optimum receiver for the linear channel, we may state that NLR is able to cancel almost all nonlinear ISI terms. In fact, NLR achieves performance close to the optimum nonlinear receiver described in [8].

5 CONCLUSIONS

In this work we have addressed the problem of optical channel equalization in the presence of nonlinear effects, described with a second order Volterra model. In particular, we proposed and analyzed an innovative Non Linear Receiver (NLR) that achieves better performance than the traditional MLSE, which is the optimum receiver for linear channels. NLR outperforms also symbol by symbol equalizers for nonlinear channels (NAVE and NDFE). The performance of NLR is close to optimum, with a reasonable computational complexity.

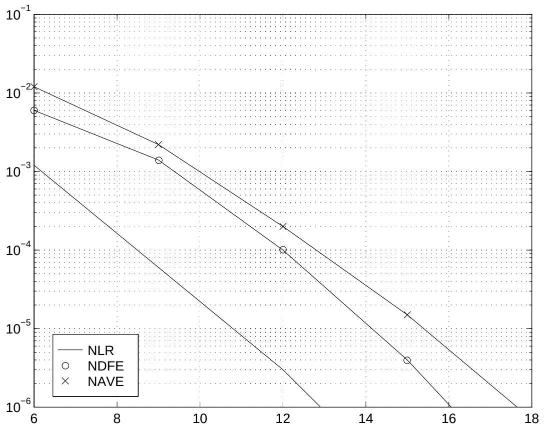

Figure 3: Performance comparison of NAVE, NDFE and NLR at the CDDA density

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