AN EFFECTIVE NON LINEAR RECEIVER FOR HIGH DENSITY OPTICAL DISC

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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

To increase the information density on optical discs, we can either augment the operating spatial frequency or decrease the track pitch (i.e., the distance between adjacent tracks). However, in high density systems the read-out signal is significantly affected by Inter-Symbol Interference (ISI) and cross talk (XT) among adjacent tracks, respectively.

In [1] we did a preliminary investigation of possible equalization algorithms, assuming a simple linear model for the optical channel. As the results we got were encouraging, we turned to more accurate channel models. In fact, in case of high density recording, 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, based on the optical scalar theory, was developed by Hopkins [3]. Using the same approach, in [4] we implemented the optical physical model. Our goal, however, was to eventually identify a nonlinear analytical model based on the Volterra series, since this is much faster to work with, and gives considerable insight into possible equalization strategies [5].

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) [6], Nonlinear Decision Feedback Equalizer (NDFE) [7] and traditional MLSE [8] for linear channels. The proposed NLR shows significant performance improvement with respect to all other algorithms, especially 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 proposed NLR, whereas simulation results are discussed in Section 4. Concluding remarks are given in the final section.

2. THE OPTICAL DISC MODEL

In short, Hopkins’s analysis [3] is based on the concatenation of the following facts. Light, generated by the laser source, propagates through the lens towards the disc surface. According to the scalar theory, field propagation is described by the Fourier transform of the scalar input field. Then, disc reflectivity is modeled making use of the Fourier series analysis for periodic structures. Light is reflected in proportion to the phase profile of the disc, times the incident field. Then the field is back-propagated to the detector (usually through the same lens as in the forward path). Back-propagation can be modeled by another Fourier transform. Finally, the photodiode converts the incident field into the electrical signal.

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 behavior of the high density optical disc, a mathematical model based on a Volterra series was considered [4] [5].

The functional input output relationship $y(t) = f[x(t)]$ can be represented as [9]:
Since it bases the decision on the entire transmitted sequence, we analyzed Maximum Likelihood Sequence Estimation (MLSE) and Decision Feedback Equalization (DFE). Then, decision, like minimum Mean Square Error (MSE) equalization (i.e., ranking) of equalization techniques.

If we associate the amplitudes 0 and 1 to lands and pits recorded on the disc, the test sequences consist of two short pits at appropriate locations.

The output signal of the physical model has been compared with the output of the nonlinear model based on the Volterra series for an EFM (Eight to Fourteen Modulation) sequence input signal, and the CDDA standard parameters (the minimum pit or land length is 0.9µm), and at increased densities. The output signals obtained from the optical model and from the Volterra series coincide, as expected. Simulations have shown that, even at the CDDA density, the contributions of second order terms are not negligible, and that nonlinear ISI becomes worse as the information density is increased [5].

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.

For the sake of simplicity, in this work we assume that noise is white, additive, and Gaussian. This AWGN model is not the most accurate one, but allows a simple comparison (i.e., ranking) of equalization techniques.

First, we studied the performance of traditional receivers for linear channels based on symbol by symbol decision, like minimum Mean Square Error (MSE) equalization and Decision Feedback Equalization (DFE). Then, we analyzed Maximum Likelihood Sequence Estimation (MLSE) [8].

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 [11]. In this situation, equalizers specifically studied for nonlinear channels, like Nonlinear Adaptive Volterra Equalizer (NAVE) [6] and Nonlinear Decision Feedback Equalizer (NDFE) [7], achieve performance close to MLSE, with lower complexity [11]. 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 [11].

On the other hand, the optimum sequence estimator for nonlinear channels [9] 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 modified Viterbi Detector (VD), which makes use of modified metrics, according to the presence of nonlinearity [9]. Fortunately, strong simplifications 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

$$r(t) = y(t) + n(t)$$  \hspace{1cm} (2)

The signal $y(t)$, which can be derived from Volterra kernels (Eq. 1), neglecting the zero-th order kernel $h_0$ can be rewritten in the form

$$y(t) = y_1(t) + y_2(t)$$  \hspace{1cm} (3)

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

Maximum likelihood sequence estimation requires that the likelihood function $\lambda$ be maximized with respect to all possible transmitted sequences. In presence of AWGN, $\lambda$ can be expressed as follows:
\[
\lambda = \frac{2}{N_0} \int y(t)r(t)dt - \frac{1}{N_0} \int y^2(t)dt \quad (4)
\]

Substituting Eqs. 2 and 3 in Eq. 4 we obtain the form of the likelihood function in the case of the nonlinear optical channel, described by a second order Volterra kernel, namely

\[
\lambda = \frac{2}{N_0} \int y_1(t)r(t)dt + \frac{2}{N_0} \int y_2(t)r(t)dt
- \frac{1}{N_0} \int y_1^2(t)dt - \frac{1}{N_0} \int y_2^2(t)dt
- \frac{2}{N_0} \int y_1(t)y_2(t)dt \quad (5)
\]

Let us denote the five terms in Eq. 5 by \(\alpha_1, \alpha_2, \beta_1, \beta_2, \beta_{12}\) respectively, i.e.,

\[
\lambda = \alpha_1 + \alpha_2 + \beta_1 + \beta_2 + \beta_{12} \quad (6)
\]

The terms \(\alpha_1\) and \(\beta_1\) in Eq. 6 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 [8]. The terms \(\alpha_2, \beta_2\) and \(\beta_{12}\) in Eq. 6, on the other hand, represent additional contributions due to nonlinearity. The term \(\beta_2\), namely the energy of the second order distortion, is a fourth order contribution that can be neglected. The third order term \(\beta_{12}\) 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. Then, the only relevant nonlinear term in Eq. 6 is \(\alpha_2\), which takes into account the presence of nonlinear ISI.

Hence, if we can remove nonlinear intersymbol interference 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 [8]. To extend the MLSE structure to the nonlinear optical channel, we may add a Non-Linear Volterra C 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

\[
z_n = \sum_{i=1}^{N} g_i r_i \quad (7)
\]

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 \[8\]

\[
g_i^{(n+1)} = g_i^{(n)} - \theta e_{n} r_i^{(n)}, \quad 1 \leq i \leq N \quad (8)
\]

\[
s_i^{(n+1)} = s_i^{(n)} + \phi (e\bar{a}_{n-D} + e\bar{a}_{n+M}), \quad 1 \leq l \leq M \quad (9)
\]

For nonlinear intersymbol interference suppression, the samples \(r_i\) should be processed by a nonlinear combiner, whose outputs are all possible products of couples of samples \(r_{h,k}\), \(1 \leq h \leq N, 1 \leq k \leq N\). 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 output \(e_n\), at the \(n\)-th iteration, is given by

\[
e_n = z_n - \sum_{i=-M}^{+M} s_i a_{n-i} \quad (10)
\]

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

\[
w_i^{(n+1)} = w_i^{(n)} - \delta \bar{e}_{n} u_i^{(n)}, \quad 1 \leq i \leq N^2 \quad (12)
\]

where \(\delta\) is the algorithm updating step, and \(\bar{e}_n\) is the signal error derived with the estimation delay \(D\):

\[
\bar{e}_n = e_n - a_{n-D} \quad (13)
\]

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

\[
h_n = e_n + z_n \quad (14)
\]

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

Fig. 1 shows a simplified block diagram of the proposed NLR. In particular, updating of the adaptive matched filter coefficients, and of the autocorrelation estimator, is not shown.
4. SIMULATION RESULTS

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, the bit energy 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).

To give an idea of the effects of second order terms, we have evaluated the performance of the MLSE considering both the second order nonlinear Volterra model, and the linear model derived neglecting second order contributions.

The performance degradation due to non-linearity is relevant, as shown in Fig. 2. The MLSE analyzed here uses an adaptive matched filter with $N = 11$ taps and a trellis memory $M = 30$.

Fig. 3 shows the NLR performance versus $E/N_0$ for different information densities, ranging from the CDDA density to twice as much.

Fig. 4 shows a comparison of NLR, NAVE, NDFE and MLSE, at the CDDA density. MLSE would be the optimum receiver if the channel were linear. Due to nonlinear distortion, yet, the performance of MLSE is not so good, in particular at high SNR values (i.e., when nonlinear distortion is the main impairment). In fact NLR, which estimates the data sequence after cancelling most second order terms, offers a significant improvement. NLR performs also significantly better than symbol by symbol equalizers designed for nonlinear channels, namely NAVE and NDFE. The performance improvement is even more impressive than shown in Fig. 4 at higher information densities.

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 model. Assuming the BER value of $10^{-5}$ as a reference, the 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
Figure 4: Performance comparison of NLR, NAVE, NDFE, and MLSE at the CDDA density.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NLR</th>
<th>simpl. NLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear taps</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>nonlinear taps</td>
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<td>11</td>
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<tr>
<td>number of states</td>
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<td>32</td>
</tr>
<tr>
<td>path truncation length</td>
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<td>15</td>
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</tbody>
</table>

Table 1: Parameters of the NLR and the simplified NLR.

Finally, we mention that a substantial complexity reduction can be obtained using a simplified NLR with a reduced number of linear and nonlinear taps, and a trellis for the VD with a reduced number of states and limited path truncation length. Considering the set of parameters shown in Tab. 1, the $E/N_0$ degradation is less than 1 dB (up to BER = $10^{-3}$).

5. CONCLUSIONS

In this work we have addressed the problem of optical channel equalization in presence of additive white Gaussian noise and of nonlinear effects, that are well 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.

6. REFERENCES


