CHARACTERIZATION OF TWO-DIMENSIONAL DIGITAL STORAGE SYSTEMS

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ABSTRACT

In this paper a channel model is proposed for two-dimensional digital data storage systems. This channel model describes both the intersymbol interference structure and the noise structure. This noise structure is modelled as the output of a two-dimensional data-dependent autoregressive filter. The proposed model is simple, accurate and it is able to track channel variations. An experimental two-dimensional optical system is used to validate the proposed model and to illustrate the characterization process based on the model.

1. INTRODUCTION

Modelling high density recording effects, particularly linear and nonlinear Intersymbol Interference (ISI) and media noise correlation has been the subject of intensive research interest in recent years. The typical tradeoff in modelling is accuracy for tracking speed, with detailed but computational intensive models [1] on one end of the spectrum and fast parametric models [2] on the other end. For two-dimensional (2D) systems a parametric model of the (nonlinear) ISI structure is described in [3]. Here we propose a more extensive model for 2D systems that, besides the ISI structure, is able to accurately describe the noise structure. The proposed model is the equivalent of the model described in [2] and is based on a signal-dependent autoregressive (AR) noise structure. It matches the observed waveform up to the second order statistics. When the noise is Gaussian, the first and the second order statistics uniquely define the probability distribution.

The proposed 2D model has several distinct features. 1) It is conceptually simple and computationally efficient. 2) Estimation of the model parameters is based on a simple data-aided adaptive scheme which achieves a high accuracy and moreover is able to track channel variations. 3) Agreement with experimental data is very good not only for the second-order statistics but also for the detection error-rates comparison.

In this paper we will describe characterization of an experimental 2D system based on the proposed model. In general, the aim of characterization is to analyze the signal waveforms of an experimental system. Characterization serves three purposes: 1) to monitor the quality of the mastered media (e.g. pit imperfections), 2) to interpret the characterization information in order to fine-tune the experimental read-out system and 3) to provide information for possible improvements in the signal processing algorithms of the receiver scheme. To serve the latter purpose, the characterization is built on the existing detection scheme.

An experimental 2D optical storage system, called TwoDOS [4], is used to illustrate the characterization process based on the proposed model. The outputs of the characterization (i.e. the values of the estimated parameters) yield important information about the ISI structure and the physical noise sources in the TwoDOS system.

The 2D channel model on which the characterization is based is presented in Section 2. In Section 3 a data-aided adaptive scheme is presented to accurately estimate the parameters of the proposed model. Finally, in Section 4 characterization of the experimental TwoDOS receiver is performed and the outputs of this characterization are shown and discussed.

Notation Throughout the paper underlined lowercase characters are used for column vectors. Uppercase boldface letters represent matrices. If $\{\underline{x}_k\}$ denotes a discrete-time sequence of vectors (k denotes time), then the matrix collecting the vectors $\underline{x}_{k+I}, ..., \underline{x}_k, ..., \underline{x}_{k-I}$ (where I is defined in the text), is denoted as

$$\mathbf{C}_k = [\underline{x}_{k+I}, ..., \underline{x}_k, ..., \underline{x}_{k-I}].$$

2. TWO-DIMENSIONAL CHANNEL MODEL

In 2D storage systems the data bits are stored on a number of parallel tracks. The 2D AR channel model of the central track ($r = 2$) is depicted in Fig. 1 for $R = 5$ tracks. The output of the discrete-time channel model at time k for track r is

$$z_k^r = x_k^r + n_k^r,$$

where x_k^r is the noiseless signal value and n_k^r is additive noise. The signal x_k^r depends on all the channel input bits in $\mathbf{C}_k = [\underline{a}_{k+I}, ..., \underline{a}_{k-I}]$, with $\underline{a}_k = [a_k^0 a_k^1 ... a_k^{R-1}]^{\mathrm{T}}$ ($a_k^r \in \{0, 1\}$) and $2I + 1$ is a suitable window dependence length that covers all intersymbol interference (ISI). To include nonlinearities, x_k^r can be constructed as a look-up-table (LUT) rather than the more common convolution between the input symbols and a linear channel response. However, because this

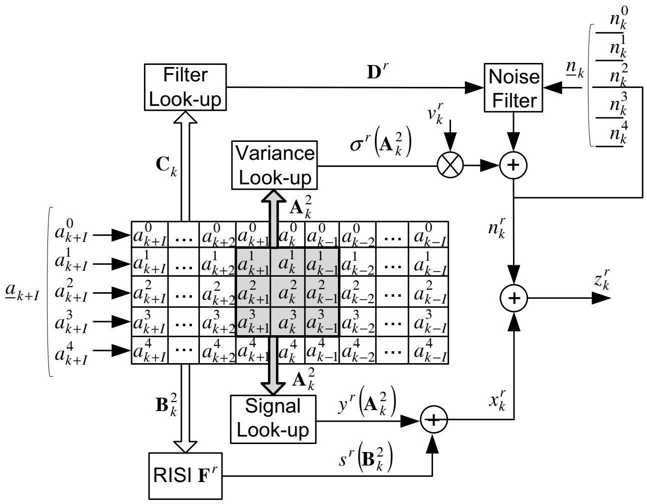


Fig. 1. Two-dimensional AR channel model for $R = 5$ tracks, shown for the central track $r = 2$.

table has a very high number of entries ($2^{R(2I+1)}$), we propose to use a combination of a LUT that encapsulates the main nonlinearities (which originate from a subset of $\mathbf{C}_k$) and a linear 2D convolution that generates the signal due to residual intersymbol interference (RISI) originating from the remaining input bits. The signal output x_k^r can then be expressed as the sum of the output of the LUT y_k^r and the RISI signal s_k^r which is the convolution output. Because the bulk of the nonlinear ISI is induced by bits close to the central bit a_k^r, the dependence window for the LUT is centered around this bit. This window of the LUT is described by the matrix $\mathbf{A}_k^r$. In this paper, the signal dependence window is chosen to cover all bits that are adjacent to the current bit, i.e. $\mathbf{A}_k^2 = [a_{k+1}^1, a_k^1, a_{k-1}^1; a_{k+1}^2, a_k^2, a_{k-1}^2; a_{k+1}^3, a_k^3, a_{k-1}^3]$. As a result for every track r, the LUT has $2^9 = 512$ entries.
The RISI signal s_k^r is computed by convolving the bits of C_k which are not in $\mathbf{A}_k^r$ (these bits are described by the matrix $\mathbf{B}_k^r$) with the RISI impulse response $\mathbf{F}^r$. Hence, the impulse response $\mathbf{F}^r$ has $R(2I-1) - 9$ nonzero coefficients. Summarizing for every track r, a LUT and a 2D impulse response $\mathbf{F}^r$ is used to characterize the noiseless signal output x_k^r.
The channel model generates, besides a signal output x_k^r, also a noise output n_k^r for every track r at every k. This noise output is modelled as the output of a causal 2D AR filter (denoted as a noise filter in Fig. 1) with an impulse response $\mathbf{D}^r$, where every coefficient $d_{i,j}^r$ ($i \in [0, R-1]$ and $j \in [1, L]$, where L is the noise memory length) is data-dependent. To limit the complexity these coefficients are considered to be dependent only on a subset of $\mathbf{C}_k$. Here the choice is made to make the coefficient $d_{i,j}^r$ depend on the window described by $\mathbf{A}_{k-j}^i$. Although this window does not cover all bits, in most cases it provides sufficient data-dependency. The noise output n_k^r can be written as the output of a 2D AR filter with at its input a white Gaussian noise sequences $\{v_k^r\}$ (with zero-mean and unit-variance):

$$n_k^r = \sum_{i=0}^{R-1} \sum_{j=1}^{L} d_{i,j}^r(\mathbf{A}_{k-j}^i) n_{k-j}^i + \sigma^r(\mathbf{A}_k^r) v_k^r,$$

where the coefficients of the noise filter, i.e. the standard deviation $\sigma^r(\mathbf{A}_k^r)$ and all tap-weights $d_{i,j}^r$ (with $i \in [0, R-1]$ and $j \in [1, L]$), are data-dependent. This noise structure makes the noise sequence $\{n_k^r\}$ both signal-dependent and correlated (where the correlation is also signal-dependent).

3. ADAPTIVE DATA-AIDED PARAMETER ESTIMATION

In this section, the channel model parameters are estimated given the model size pair (I, L) (the data-dependence window length I and the noise correlation length L), known data sequences $\underline{a}_0 ... \underline{a}_N$ and its associated waveforms $\underline{z}_0 ... \underline{z}_N$, with $N \gg 2^{I+1}$. The waveforms are experimental replay signals that should be synchronous with respect to the baudrate. The classical approach is to compute means and covariance matrices and to calculate the model parameters $y^r(\mathbf{A}_k^r)$, $\mathbf{F}^r$, $\sigma^r(\mathbf{A}_k^r)$ and $d_{i,j}^r(\mathbf{A}_{k-j}^i)$ (for $i \in [0, R-1]$ and $j \in [1, L]$) based on these matrices, involving complex matrix operations (known as the Yule-Walker equations [2]). Because of these complex operations, the classical approach is numerically not very interesting. For this reason a method to adaptively track the model parameters directly on the experimental signals, is proposed. Moreover, tracking these parameters adaptively is preferable in many applications because the noise may be nonstationary.
The error signal e_k^r of track r at time k is defined as

$$e_k^r = z_k^r - \Big(y^r(\mathbf{A}_k^r) + s^r(\mathbf{B}_k^r) \Big).$$

At every clock cycle the signal LUT is easily updated according to

$$y^r(\mathbf{A}_k^r)^{(new)} = y^r(\mathbf{A}_k^r)^{(old)} + \mu e_k^r, \qquad (1)$$

where μ denotes the adaptation constant. The RISI impulse response coefficients $f_{i,j}^r$ (for $i \in \{0, R-1\}$, $j \in \{-I, +I\}$ and only if $a_j^i \in \mathbf{B}_k^r$) are updated according to

$$f_{i,j}^{r\,(new)} = f_{i,j}^{r\,(old)} + \mu e_k^r a_j^i. \qquad (2)$$

Define $\mathbf{W}^r = [\underline{c}^r, -\mathbf{D}^r]$, where $\underline{c}^r$ is a column vector with R elements c_i^r ($i \in [0, R-1]$)

$$c_i^r = \delta_{i-r},$$

and δ_i is the Kronecker delta function. The set of filters $\mathbf{W}^r$ (for $r = [0, R-1]$) are meant to whiten the error signals $\underline{e}_k, ..., \underline{e}_{k-L}$. As a result a scheme to estimate and to track the filter coefficients $\mathbf{D}^r$ and $\sigma^r(\mathbf{A}_k^r)^2$ can be based on minimizing the cost function $J^r = E\left[(\mathcal{N}_k^r)^2\right]$, where $\mathcal{N}_k^r$ is the whitened error signal given by

$$\mathcal{N}_k^r = e_k^r - \sum_{i=0}^{R-1}\sum_{j=1}^{L} d_{i,j}^r(\mathbf{A}_{k-j}^i)e_{k-j}^i.$$

At every clock cycle, for every track r, one variance value $\sigma^r(\mathbf{A}_k^r)^2$ and all the coefficients $d_{i,j}^r(\mathbf{A}_{k-j}^i)$ (for $j \in [0, R-1]$ and $i \in [1, L]$) are updated according to

$$\begin{array}{rcl} \sigma^r(\mathbf{A}_k^r)^{2\,(new)} & = & (1-\mu)\sigma^r(\mathbf{A}_k^r)^{2\,(old)} + \mu\mathcal{N}_k^r e_k^r, \\ d_{i,j}^r(\mathbf{A}_{k-j}^r)^{(new)} & = & d_{i,j}^r(\mathbf{A}_{k-j}^r)^{(old)} + \mu\mathcal{N}_k^r e_{k-i}^i. \end{array} \quad (3)$$

The equations (1), (2) and (3) together define the updating rules that are applied for the estimation of the different model parameters.

4. EXPERIMENTAL MULTI-TRACK OPTICAL STORAGE

An experimental multi-track optical storage system, called TwoDOS, is used to illustrate the characterization based on the proposed model. The TwoDOS system aims to achieve an increase over the 3$^{\text{rd}}$ generation discs (Blu-Ray, BR, discs) with a factor of two in capacity (50 GB) and a factor of ten in data rate (300 MB/s). In contrast with conventional optical recording (CD, DVD and BR), where the bits are stored in a single spiral (a one-dimensional sequence of bits), in TwoDOS the bits are organized in a so-called broad spiral. In Fig. 2 the broad spiral is shown. The broad spiral contains seven bit tracks (R=7), stacked upon each other to form a hexagonal structure. Besides the hexagonal structure, also the grouping of bits into shells is shown in Fig. 2. Bits with an identical distance to the central bit are numbered identically. The $x-$axis is denoted as the tangential direction (i.e. parallel with broad spiral) and the $y-$axis is denoted as the radial direction (i.e. orthogonal to the broad spiral). The data is read out with an array of R laser spots arranged such that each spot is centered on one of the bit tracks within the broad spiral. A multi-spot photo detector integrated circuit is used to generate a so-called high-frequency (HF) signal for every bit track. A PRML receiver has been built for TwoDOS [4]. It consists of a bit detector preceded by an adaptive equalizer, an adaptive DC compensator, an AGC and a timing recovery loop. The purpose of the adaptive equalizer is for every track r to shape the ISI structure induced by the channel into a predefined linear ISI structure, denoted as the target response g_0. Because at the detector input the bulk of the ISI energy is concentrated within the span defined by the target response (typically this span covers all bits within the first shell, see Fig. 2), the signal LUT is implemented to incorporate this energy, i.e. the LUT of $y^r(\mathbf{A}_k^r)$ has $2^7 = 128$ entries. If due to misequalization, not all the ISI is incorporated into the target span, some RISI

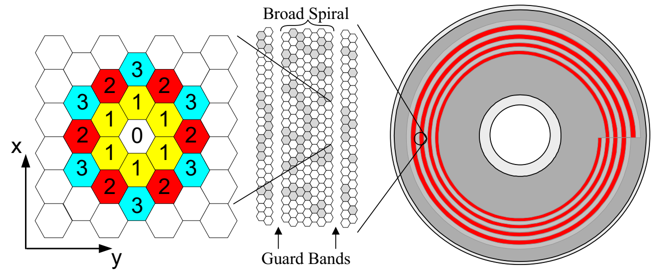


Fig. 2. Schematic TwoDOS disc format (right part) and hexagonal bit pattern illustrating 3 adjacent shells (left part).

is left outside the span of the target. This RISI is characterized by the impulse response $\mathbf{F}^r$.

A 2D VD performs joint bit detection on all bit tracks based on the values in the LUT entries $y^r(\mathbf{A}_k^r)$. To reduce the complexity of a full-fledged 2D VD, the VD is divided into smaller processing units (called stripe VD). Each stripe VD covers a limited number of bit tracks (so-called stripes with a typical height of 2 or 3 bit tracks). This detection configuration is called a stripe-wise viterbi detector (SWVD) [4].

Characterization of the experimental TwoDOS system is based on the read-out of a 50 GB single layer disc. The actual characterization is performed on the input signals of the SWVD. The AR channel model is defined as follows: $I = 7$ and $\mathbf{A}_k^r$ contains the 7 bits within the first shell. Furthermore to limit the number of model parameters (i.e. the number of LUTs that are needed) the noise filter $\mathbf{D}^r$ has only 3 non-zero taps: namely the taps within the first shell which are causal (see Fig. 2). In Subsection 4.1 the proposed AR channel model will be validated. Finally, in Subsection 4.2 the values of the estimated model parameters are shown and discussed.

4.1. Model Validation

The real test of the proposed channel model is the bit error rate (BER) comparison presented in Fig. 3. HF signals coming from the experimental set-up are applied to the TwoDOS receiver to produce equalized synchronous inputs of the SWVD. These inputs were used to estimate the parameters of the proposed channel model. The error rates in Fig. 3 present the performance of the SWVD for the real noisy experimental data, the data generated by applying the proposed channel model and the data generated by applying a channel model that has the same ISI structure but generates only white noise (with $\sigma^r = E[(e_k^r)^2]$). The first bars compare the overall BER, while the other bars compare the BER due to error events with a specific length. The data-dependent AR channel model is clearly a more accurate model than the white noise model. Because the white noise model does not take the noise coloration into account, it produces BERs that are too optimistic.

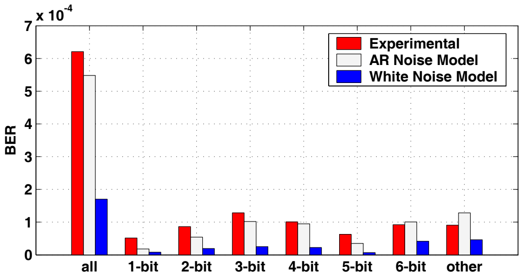
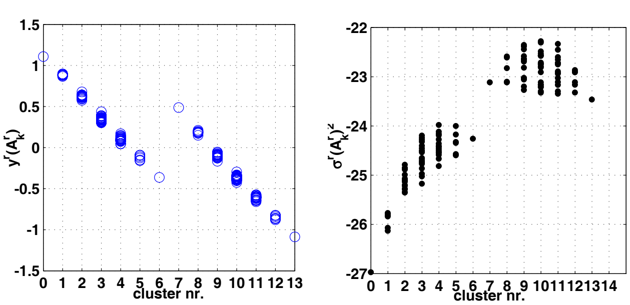


Fig. 3. Error rate comparison between experiment, data-dependent AR channel model and white noise channel model.

4.2. Estimated Model Parameters

The signal values $y^r(\mathbf{A}_k^r)$ (128 values in total) are plotted versus cluster number in Fig. 4(a) for the central track $r = 3$, where cluster number is defined as $7a_k^r + \sum_{j,i\in\mathbf{A}_k^r} a_i^j$. The plot shows two branches: the left branch corresponds to clusters with $a_k^r = 0$ and the right branch corresponds to clusters with $a_k^r = 1$. In Fig. 4(b) the signal-dependent variances $\sigma^r(\mathbf{A}_k^r)^2$ are plotted versus the cluster number for track $r = 3$. The observation that the right branch has higher variances than the left branch, indicates that pit size variations are the dominant sources of media noise in the optical recording process. A noise-predictive maximum likelihood detector can be used to improve the overall system performance. This detector uses the estimated correlation filters to whiten the noise in the detector [5]. The estimated signal-dependent noise variances can be used in the computation of a modified branch metric to improve the performance even further [5].

The noiseless signal output is obtained by summing $y^r(\mathbf{A}_k^r)$ and the RISI value s_k^r. The RISI impulse response $\mathbf{F}^r$ is shown in Fig. 5 for $r = 3$ in case there is an angle between the disc and the laser beam of $-1.0°$ in the radial direction. The RISI components are limited in amplitude. Furthermore RISI originating from symbols with limited temporal separation from the symbols of the target response is non-negligible. This RISI hampers the performance of the SWVD considerably and it suggests some extra measures against RISI should be taken (e.g. ISI cancellation).



(a) Signal values. (b) Noise variances.

Fig. 4. Estimated parameters for the central track $r = 3$.

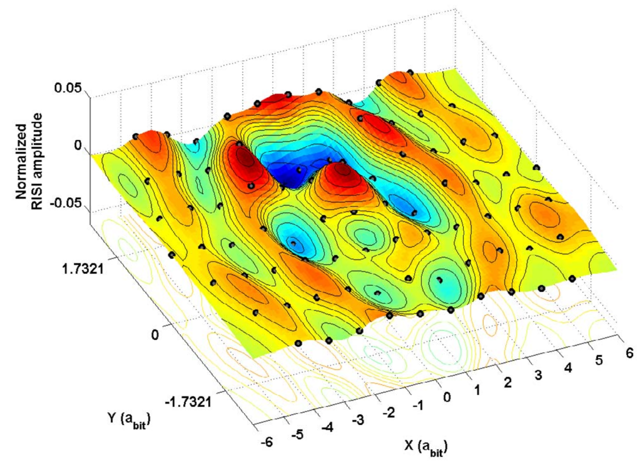


Fig. 5. Estimated amplitudes (normalized with respect to $E[|y^r(\mathbf{A}_k^r)|]$) of the RISI impulse response $\mathbf{F}^r$ at the detector input for $r = 3$ ($\mathbf{F}^r$ is centered around track $r = 3$). Both axis are scaled in terms of $\mathrm{a_{bit}}$, where $\mathrm{a_{bit}}$ is the distance between two bits measured on the disc ($\mathrm{a_{bit}} = 138$ nm for 50 GB disc).

5. CONCLUSION

In this paper a signal-dependent channel model for multi-track storage systems was presented with (nonlinear) intersymbol interference and signal dependent and correlated media noise. Several attractive features of this model were demonstrated: simplicity, straightforward parameter estimation and direct relationship with receiver optimization. An experimental multi-track optical system was used to demonstrate the accuracy of the model.

6. REFERENCES

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