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Iterative Decoding for High-Density Bit-Patterned Media Recording

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Abstract

Bit-patterned media recording (BPMR) is one of the promising techniques to be used to achieve the areal density beyond the super-paramagnetic limit. Nonetheless, the BPMR system is normally encountered both inter-symbol interference and inter-track interference, especially at high recording densities. This problem is regarded as one of the most challenging issues in the BPMR system. In this paper, we design a two-dimensional (2D) cross-track symmetric target and its corresponding equalizer to combat both interferences. Furthermore, we also utilize an iterative scheme, which iteratively exchanges soft information between a 2D SOVA detector and an LDPC decoder, to decode an input data sequence. Results indicate that the proposed method performs better than other methods, especially when the recording density is high.

Keywords: 2D SOVA; bit-patterned media; inter-track interference; target and equalizer design

1. Introduction

The need for higher areal densities in perpendicular magnetic recording can be answered by continually reducing the magnetic grain size. Although this technique offers an increase in storage capacity, a major problem of using this technique is that reducing the grain size could lead to severe noise in a system, and consequently low signal-to-noise ratio (SNR) is expected. As a result, continually reducing the grain size will not always be possible. In fact, the maximum achievable areal density offered by reducing the magnetic grain size is bounded by the superparamagnetic limit [1]. On the other hand, a bit-patterned media

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recording (BPMR) technique has become of interest from researchers around the world. This is because BPMR is capable of increasing the areal density beyond the superparamagnetic limit. As reported in [2], it is possible to achieve the areal density of up to 4 Tb/in^2 (Tera-bit per square inch) based on BPMR.

In BPMR, a data bit is stored in a single magnetic island with a narrow track (i.e., the center-to-center track distance is less than 18 nm). Thus, the areal density can be increased tremendously if compared with the capacity that perpendicular magnetic recording (PMR) can offer. However, the use of a single magnetic island with a narrow track width causes the problem of inter-symbol interference (ISI) and inter-track interference (ITI), which can lead to performance degradation if precautions are not taken. Additionally, BPMR can also encounter write synchronization error, media noise, and track mis-registration, which even worsen system performance. Hence, a good read-channel design must be able to provide robustness and reliability to combat these issues. Even though two interferences are occurred in BPMR, this paper focuses only on how to eliminate the ITI. The ISI suppression is not discussed here because it has already been widely studied in PMR's equalizer designs [5]. Practically, the ITI results from the use a narrow track pitch. For example, an ultra high areal density will correspond to the system with a very narrow track pitch, and thus the ITI can be expected to be quite severe.

There are many existing techniques designed to overcome the ITI. Nabavi [1] proposed the use of 1D generalized partial response (GPR) target and 1D equalizer for a single-head BPMR system to mitigate the ITI. However, this technique is not suitable for a high-density BPMR system because it cannot work well in the presence of severe ITI. Karakulak [3] also proposed the use of a zero-corner 2D target with a 1D equalizer to combat the ITI effect, where the 2D Viterbi detector is used to decode data in this design. This paper proposes the design of a 2D cross-track symmetric target and its corresponding 1D equalizer that are suitable for high areal density BPMR (i.e., 3 – 4 Tb/in^2). Moreover, we introduce an iterative scheme, which iteratively exchanges soft information between the 2D SOVA detector and the LDPC decoder, to decode an input data sequence.

The rest of this paper is organized as follows. Section 2 briefly describes the BPMR channel model. The design of a 2D cross-track symmetric GPR target is explained in Section 3. Section 4 presents how the 2D SOVA detector performs. Simulation results are given in Sections 5. Finally, Section 6 concludes this paper.

2. Channel Model

In BPMR, the 2D pulse response depends on the characteristics of magnetic islands that are uniformly distributed on the media. All parameters used in modeling the BPMR channel [1] are summarized in Table 1, where the 2D Gaussian pulse response $H(x,z)$ can be approximated by

$$H(x,z) = A\exp\left\{-\frac{1}{2}\left(\frac{x^2}{w_x^2}+\frac{z^2}{w_z^2}\right)\right\}, \tag{1}$$

where $A = 1$ is amplitude of a 2D pulse response, $w_x = W_x/2.5348$, $w_z = W_z/2.5348$, W_x is an along-track PW_{50}, and W_z is an cross-track PW_{50}. In a discrete-time equivalent channel, the coefficients of a channel matrix (**H**) are obtained by sampling (1) at bit period (T_x) and the track pitch (T_z). In general, an areal density of BPMR is limited by T_x and T_z, which is equal to $1/T_xT_z$ in bit per square inch [6].

Consider a coded BPMR channel model in Fig. 1, where we assume that only two adjacent tracks cause most of ITI. A binary input sequence $a_{k,m} \in \{0,1\}$ of length 3640 bits is encoded by a rate-8/9 low-density parity-check (LDPC) code [7] and is mapped to a data block of 4095 bits $u_{k,m} \in \{\pm 1\}$ with bit period T_x, where $m = 0$ represents the main track, $m = \pm 1$ represents the closet adjacent track, and k is the k-th bit. Then, the readback signal can be written as

Table 1. The media and the MR head parameters that are used in the BPMR channel model.

Name of the parameter	Parameter	Default value (nm)
Square island (each side)	a	11
Thickness	δ	10
Fly height	d	10
Thickness of the MR head	t	4
Width of the MR head	W	16
Gap to gap width	g	16
Along-track PW_{50}	W_x	19.8
Cross-track PW_{50}	W_z	24.8

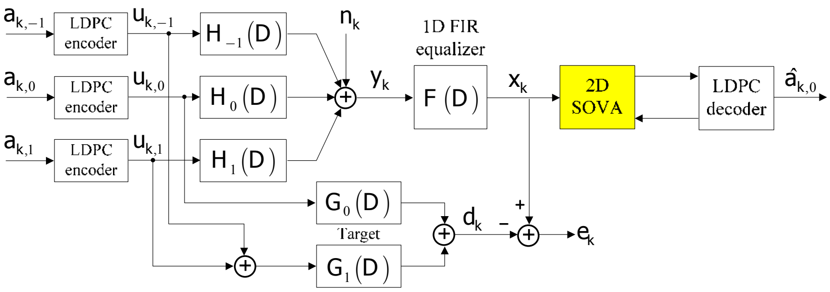

Fig. 1. A BPMR channel model with 1D equalizer and 2D target design

$$y_k = \sum_i \sum_m h_{i,m} u_{k-i,m} + n_k \tag{2}$$

where $H_m(D) = \Sigma_i h_{i,m} D^i$ is the channel of the m-th track [1], $h_{i,m}$'s are the 2D channel response coefficients, D is a unit delay operator, and n_k is AWGN with zero mean and variance σ^2. We assume that the system has perfectly synchronization and media is uniform without TMR effect.

At the receiver, the sequence y_k is equalized to a 2D cross-track symmetric target $G_m(D)$ by a 1D equalizer such that x_k resembles d_k, where $G_m(D) = \Sigma_i g_{i,m} D^i$ is the target of the m-th track and $h_{i,m}$'s are the 2D target response coefficients. Finally, the sequence x_k is fed to a turbo equalizer [8], which iteratively exchanges soft information between the 2D SOVA equalizer and the LPDC decoder implemented based on a message passing algorithm with 3 internal iterations.

3. Target and Equalizer Design

In general, at the areal density below 2.5 Tb/in^2, the ITI coefficients are small and can be negligible, thus making it possible to use a 1D target or a zero-corner 2D target in the BPMR system. However, the use of a 2D cross-track symmetric target is not suitable for the system with low areal densities because it does not offer any significant gain to the system performance but instead introduces very high complexity to the system. This is because the ITI coefficients become significant at high areal densities (beyond 2.5 Tb/in^2), and thus the ITI effect can no longer be overlooked.

To handle severe ITI properly, the 2D target with zero-corner [3] cannot perform reliably. Without the TMR and media noise, this paper proposes the design of the 1D equalizer $F(D)$ and its corresponding 2D target with cross-track symmetry based on minimizing a mean-squared error (MSE) between x_k and d_k. The 2D target is given in a 3×3 matrix form as

$$\mathbf{G} = \begin{bmatrix} \mathrm{G}_{-1}(D) \\ \mathrm{G}_0(D) \\ \mathrm{G}_1(D) \end{bmatrix} = \begin{bmatrix} g_{0,-1} & g_{1,-1} & g_{2,-1} \\ g_{0,0} & g_{1,0} & g_{2,0} \\ g_{0,1} & g_{1,1} & g_{2,1} \end{bmatrix} \quad (3)$$

where $G_{-1}(D) = G_1(D)$. Let $F(D) = \sum_{i=-M}^{M} f_i D^i$ denote a 1D equalizer of $2M+1$ taps whose center tap is at $M+1$. Therefore, the difference between x_k and d_k can be written as $e_k = x_k - d_k = f_k * y_k - g_{k,m} * u_{k,m}$, where $*$ is a convolution operator.

Let $\mathbf{g} = [g_{0,-1}\ g_{0,0}, g_{1,-1}\ g_{1,0}\ g_{2,-1}\ g_{2,0}]^{\mathrm{T}}$ be a 6×1 column vector of $\mathbf{G}$, where $g_{1,0}$ is set to 1, $\mathbf{f} = [f_{-M} \ldots f_0 \ldots f_M]^{\mathrm{T}}$ be a $(2M+1)\times 1$ column vector of $F(D)$, $\mathbf{u_k} = [(u_{k,-1} + u_{k,1})\ u_{k,0}\ (u_{k-1,-1} + u_{k-1,1})\ u_{k-1,0}\ (u_{k-2,-1} + u_{k-2,1})\ u_{k-2,0})]^{\mathrm{T}}$ be a 6×1 column vector of an input data sequence, and $\mathbf{y_k} = [y_{k+M}, \ldots y_k, \ldots y_{k-M}]^{\mathrm{T}}$ be a $(2M+1)\times 1$ column vector of an equalizer input sequence. Thus, the MSE can be expressed as

$$E[e_k^2] = E[(\mathbf{f}^{\mathrm{T}}\mathbf{y_k} - \mathbf{g}^{\mathrm{T}}\mathbf{u_k})^2], \quad (4)$$

where $E[.]$ is an expectation operator. During the minimization process, we use a constraint of $\mathbf{I}^{\mathrm{T}}\mathbf{g} = 1$ to avoid reaching a solution of $\mathbf{f} = \mathbf{g} = 0$, where $\mathbf{I} = [0\ 0\ 0\ 1\ 0\ 0]^{\mathrm{T}}$. Consequently, adding this constraint to (4) yields

$$E[e_k^2] = \mathbf{f}^{\mathrm{T}}\mathbf{U}\mathbf{f} - 2\mathbf{f}^{\mathrm{T}}\mathbf{T}\mathbf{g} + \mathbf{g}^{\mathrm{T}}\mathbf{R}\mathbf{g} - 2\lambda(\mathbf{I}^{\mathrm{T}}\mathbf{g} - 1), \quad (5)$$

where λ is a Lagrange multiplier, $\mathbf{U} = E[\mathbf{u_k}\mathbf{u_k}^{\mathrm{T}}]$, a 6×6 auto-correlation matrix of a sequence $\{u_k\}$, $\mathbf{R} = E[\mathbf{y_k}\mathbf{y_k}^{\mathrm{T}}]$ is a $(2M+1)\times(2M+1)$ auto-correlation matrix of a sequence $\{y_k\}$, and $\mathbf{T} = E[\mathbf{y_k}\mathbf{u_k}^{\mathrm{T}}]$ is a $(2M+1)\times 6$ cross-correlation matrix of sequences $\{y_k\}$ and $\{u_k\}$. By minimizing (5), the 2D target and its corresponding 1D equalizer can be computed as

$$\lambda = 1/\left(\mathbf{I}^{\mathrm{T}}(\mathbf{U} - \mathbf{T}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{T})^{-1}\mathbf{I}\right) \quad (6)$$

$$\mathbf{g} = \lambda(\mathbf{U} - \mathbf{T}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{T})^{-1}\mathbf{I} \quad (7)$$

$$\mathbf{f} = \mathbf{R}^{-1}\mathbf{T}\mathbf{g} \quad (8)$$

4. Two-Dimensional Soft-Output Viterbi Algorithm

To perform maximum-likelihood (ML) equalization via a 2D SOVA, we use a similar technique that is employed in the bidirectional SOVA [9] to compute the log-likelihood ratio (LLR) of the bit $u_{k,0}$, i.e., $L(u_{k,0})$. For the 3×3 target matrix with cross-track symmetry, the trellis diagram of this 2D SOVA will have 36 states in total, and for each state at time k, there are 6 outgoing branches connected to 6 different states at time $k+1$.

5. Simulation Setup

In simulation, the channel coefficients $h_{i,m}$ are obtained by sampling the 2D Gaussian pulse in (1) at specific bit period (T_x) and track pitch (T_z) to achieve different areal densities. Here, we consider high areal densities at 3, 3.5, and 4 Tb/in^2, which correspond to $T_x = T_z = 14.5$, 13.5, and 13 nm, respectively. We also employ a 15-tap equalizer (i.e., $M = 7$) because increasing equalizer taps will not provide significant performance improvement. The proposed 2D target is compared with the targets proposed in [1] and [3], where the target presented in [1] is referred to as "1D target" and that presented in [3] is denoted as "2D target with zeros corner." We compute the bit-error rate (BER) based on a minimum number of 10000 data sectors and 1000 error bits.

5.1 Uncoded System

Figure 2 compares the performance of the proposed method with that of the others for an *uncoded* system (i.e., without ECC code). In this case, the signal-to-noise ratio (SNR) is defined as SNR = $10\log_{10}1/\sigma^2$ in decibel (dB), where $\sigma^2 = N_0/(2T_x)$ is AWGN power. It is evident that the 1D target performs unacceptable, especially at high areal densities. However, the proposed 2D target performs better than the others because it takes severe ITI into account when designing the 2D target. Therefore, when an areal density is high, we must not force some target coefficients to be zero when designing the target, like the 1D target and the 2D target with zeros corner.

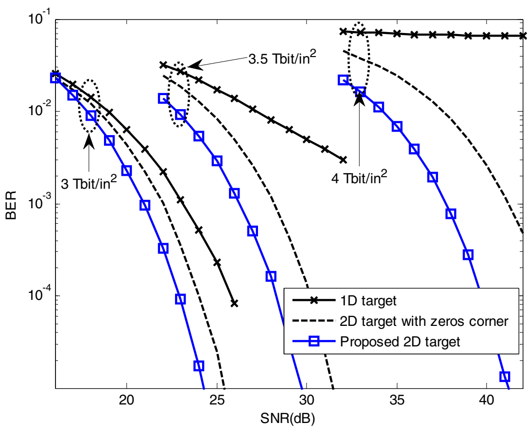

Fig. 2. BER performance with different methods in an uncoded system

5.2 Coded System

Next, we consider a rate-8/9 coded system as depicted in Fig. 1. A block of 3640 bits is encoded by a regular (3, 27) LDPC code [7], where a parity-check matrix has three 1's in each column and 27 1's in each row. The LDPC decoder is implemented based on a message-passing algorithm [7] with 3 internal iterations. In a coded system, the signal-to-noise ratio is defined as SNR = $10\log_{10}(1/(R\sigma^2))$ in dB, where $R = 8/9$ is an LDPC code rate. Figure 3 compares the BER performance of different methods in a coded system. Clearly, the proposed 2D target performs better than other targets even in a coded system. Specifically, we found that at BER $=10^{-4}$, the proposed 2D target yields a performance gain of approximately 1 dB, 3 dB, and 4 dB, when compared with the 2D target with zeros corner at 3, 3.5, and 4 Tb/in^2, respectively. Additionally, the 1D target seems to have an error floor for all areal densities.

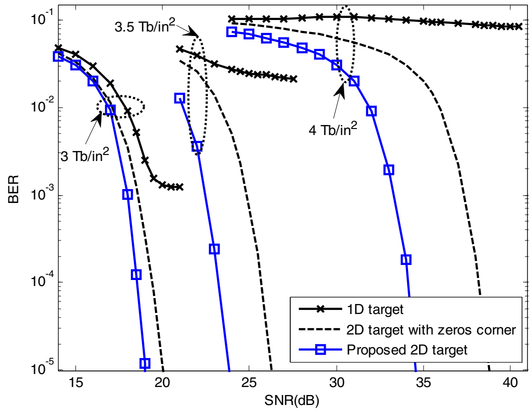

Fig. 3. BER performance with different methods in a coded systems

6. Conclusion

At high areal densities (beyond 2.5 Tb/in^2), the ISI and the ITI are very severe in the BPMR channel and can be considered as a main cause of performance degradation. Because the ISI has already been studied extensively in the literature, the ITI has not yet been addressed in other existing systems. Thus, this paper proposes the design of a cross-track symmetric target and its corresponding 1D equalizer to combat the effect of severe ITI. At the receiver, we also propose an iterative scheme, which iteratively exchanges soft information between the 2D SOVA detector and the LDPC decoder, to decode an input data sequence. Simulation results show that our proposed target is suitable for high-density BPMR system because it offers superior performance if compared to the 1D target and the 2D target with zeros corner. The performance gain (when compared with the 2D target zeros corner) can be as high as 4 dB at an areal density of 4 Tb/in^2.

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