Two-Dimensional Cross-Track Asymmetric Target Design for High-Density Bit-Patterned Media Recording

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Abstract— **In bit-patterned media recording (BPMR) channels at ultra high areal densities, the inter-track interference (ITI) is extremely severe, which significantly degrades the system performance. The partial-response maximum-likelihood (PRML) technique that uses a one-dimensional (1D) partial response target might not be able to cope with this severe ITI, especially in the presence of media noise and track mis-registration (TMR). This paper proposes a two-dimensional (2D) cross-track asymmetric target, based on a minimum mean-squared error approach, for high-density BPMR channels. Result indicates that the proposed 2D target performs better than previously proposed 2D targets especially when media noise and TMR is severe.**

Keywords—2D Target and equalizer design, Bit-patterned media recording (BPMR), Inter-track interference (ITI), Media noise, Track mis-registration (TMR)

I. INTRODUCTION

Conventional magnetic recording system is experiencing the problem of super-paramagnetic limit in the near future [1]. As a result, several researches have been recently proposed to extend the storage capacity of next generation's hard disk drives [2], which include bit-patterned media recording (BPMR), heat-assisted magnetic recording (HAMR), microwave-assisted magnetic recording (MAMR), and two-dimensional magnetic recording (TDMR). However, this paper focuses on the BPMR.

In BPMR, a data bits are stored in a single domain magnetic island, which is surrounded by non-magnetic material. Although the BPMR can increase an areal density beyond 4 Tbit/in^2 [3], it faces with new challenges in signal processing, such as two-dimensional (2D) interference, media noise, track mis-registration (TMR), and so on. The 2D interference consists of inter-symbol interference (ISI) and inter-track interference (ITI). Practically, when the areal density is high, the system will encounter severe ITI because of very narrow track pitch. In addition to the ITI, there is also an impact from media noise and TMR. Media noise is resulted from non-uniform magnetic islands with amplitude fluctuation and location fluctuation, whereas the TMR is a read-head offset occurred when the read head is not aligned at the center of the main track. Furthermore, the write synchronization error in BPMR leads to the problems of insertion/deletion and substitution in the received readback signal.

Many works have been proposed for signal detection in BPMR systems. Nabavi *et al.* [4] proposed the modified Viterbi detector, which uses the same trellis diagram as employed in a conventional (1D) Viterbi detector, to mitigation the ITI effect, and also to alleviate the TMR effect [5]. Then, Nabavi [1] has also proposed the 1D target and 2D equalizer design for multi-head BPMR system. It has shown that the 2D equalizer yields better performance than 1D equalizer at the expense of increasing complexity. Kalakulak [6] proposed a new channel model for designing the 1D equalizer and the 2D target with zero corner entries. Finally, Myint *et al.* [7] proposed an iterative decoding scheme mitigate the ITI effect for multi-head BPMR channels. Nevertheless, for the BPMR system with one read head, all recently proposed targets yield good performance at low areal densities ($\leq$ 2.5 Tbit/in^2), but perform unreliable at high areal densities because of severe ITI. It is clear that the ITI is very severe in the BPMR system at high areal densities. To cope with this severe ITI, Koonkarnkhai *et al.* [8] proposed the design of symmetric 2D target and an iterative decoding scheme to combat severe ITI. However, the symmetric 2D target is not suitable for the system that experiences media noise and TMR. Therefore, this paper presents the design of 2D cross-track asymmetric target for high-density BPMR systems, where the coefficients of the proposed 2D target are all different. We also compare the performance of the proposed 2D target with the existing 2D targets in terms of bit-error rate (BER) in the BPMR system with media noise and TMR.

This paper is organized as follows. After describing a BPMR channel used in our simulation in Section II, Section III presents the design of 2D cross-track asymmetric target and its corresponding equalizer. Simulation results are given in Section IV. Finally, Section V concludes this paper.

II. CHANNEL MODEL

Consider the BPMR channel, where the 2D numerical pulse response is obtained for a square magnetic island with length of 11 nm, thickness of 10 nm, fly height of 10 nm, and using

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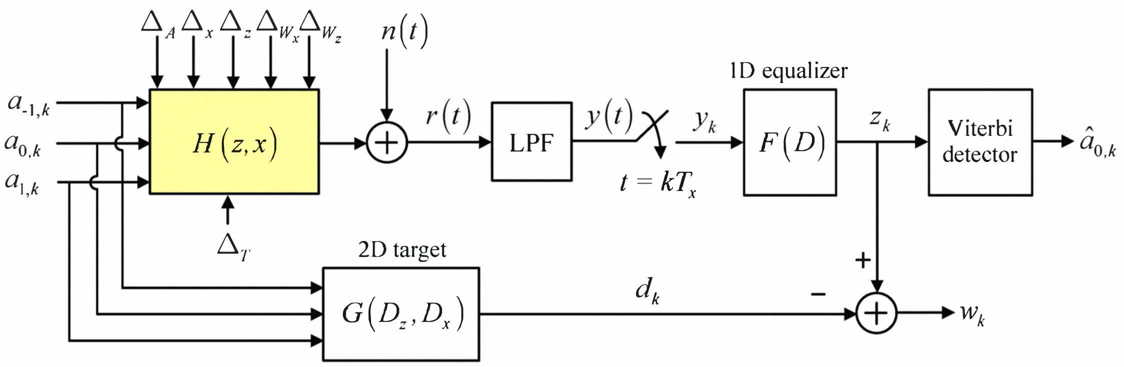

Figure 1. A channel model with 1D equalizer and 2D target design in the presence of media noise and TMR.

an MR head with an element length of 4 nm, an element width of 16 nm, and a gap-to-gap distance of 16 nm. Then, the 2D pulse response can be approximated by a 2D Gaussian pulse with media noise according to [1]

$$H(z,x)=(A+\Delta_A)\exp\left\{-\frac{1}{2}\left[\left(\frac{x+\Delta_x}{c(W_x+\Delta_{W_x})}\right)^2+\left(\frac{z+\Delta_z}{c(W_z+\Delta_{W_z})}\right)^2\right]\right\} \quad (1)$$

where $A = 1$ is the maximum amplitude, Δ_A is the amplitude fluctuation, Δ_x is the along-track fluctuation, Δ_z is the cross-track location fluctuation, W_x is the PW_{50} of an along-track pulse, W_z is the PW_{50} of a cross-track pulse, and $c = 1/2.3458$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian function. We rearrange the island rectangular grid by parameters T_x and T_z to achieve different areal densities according to [9]

$$\text{Areal density} \approx \frac{10^6}{1550T_xT_z} \quad (2)$$

in Tbit/in^2, where T_x is a bit period in nm on along-track direction and T_z is a track pitch in nm on cross-track direction.

Fig. 1 shows a channel model in the presence of media noise and TMR. An input sequence $a_{m,n} \in \{\pm 1\}$, where $m = 0$ is the main track, and $m = -1$ and $+1$ are an upper track and a lower track, respectively. The readback signal $r(t)$ can then be written as [1]

$$r(t)=\sum_{m=-1}^{1}\sum_{n=-1}^{1}a_{m,n}H(-mT_z-\Delta_T,t-nT_x)+n(t), \quad (3)$$

where $n(t)$ is additive white Gaussian noise (AWGN) with two-side power spectral density $N_0/2$. The TMR is defined as

$$\text{TMR}=\frac{\Delta_T}{T_z}\times 100, \quad (4)$$

where Δ_T is a track offset, The media noise (Δ_A, Δ_x, Δ_z, Δ_{Wx} and Δ_{Wz}) is modeled as a truncated Gaussian probability distribution function with zero mean and σ^2, where σ is specified as percentage of T_x.

The readback signal $r(t)$ is fed to a 7th-order Butterworth low-pass filter (LPF) and is sampled at $t = kT_x$, assuming perfect synchronization. The sampler sequence y_k is equalized by a 1D equalizer $F(D)$ to obtain a sequence z_k, and is then fed to the Viterbi detector to determine the most likely input sequence $a_{0,k}$.

III. 2D Target and 1D Equalizer Design

In BPMR, the target and equalizer design is of importance to improve the system performance because it can help reduce the effect of both ISI and ITI. At low areal densities, the ITI effect is very small and can be neglected. On the other hand, when the areal density is high, the ITI effect is very severe and thus cannot be ignored when designing the target and its corresponding equalizer. Clearly, at high densities, the 2D target is needed in BPMR channels to account for the severe ITI, which can be obtained as follows.

As shown in Fig. 1, we assume that the 2D target matrix is given by

$$G=\begin{bmatrix} G_{-1}(D) \\ G_0(D) \\ G_1(D) \end{bmatrix}=\begin{bmatrix} g_{-1,0} & g_{-1,1} & g_{-1,2} \\ g_{0,0} & g_{0,1} & g_{0,2} \\ g_{1,0} & g_{1,1} & g_{1,2} \end{bmatrix}. \quad (5)$$

The difference between d_k and z_k is given by $e_k = z_k - d_k = y_m{*}f_k - a_{m,k}{*}g_{m,k}$, where $*$ is a convolution operator, f_k is the k-th coefficient of an equalizer $F(D)=\sum_{i=-K}^{K}f_iD^i$ and $N = 2K+1$ is the number of equalizer taps. The column vectors of the 2D target and the equalizer can be defined as $\mathbf{g} = [g_{-1,0}\ g_{0,0}\ g_{1,0}\ g_{-1,1}\ g_{0,1}\ g_{1,1}\ g_{-1,2}\ g_{0,2}\ g_{1,2}]^T$, and $\mathbf{f} = [f_{-K} \ldots f_0 \ldots f_K]^T$, respectively, where $[.]^T$ is a transpose matrix operator. Then, a mean square error (MSE) of e_k can be expressed as

$$E[e_k^2] = E[(\mathbf{f}^T\mathbf{y}_k - \mathbf{g}^T\mathbf{a}_k)^2] = E[(\mathbf{f}^T\mathbf{y}_k - \mathbf{g}^T\mathbf{a}_k)(\mathbf{f}^T\mathbf{y}_k - \mathbf{g}^T\mathbf{a}_k)^T], \quad (4)$$

where $E[.]$ is an expectation operator, $\mathbf{a}_k = [a_{-1,k}\ a_{0,k}\ a_{1,k}\ a_{-1,k-1}\ a_{0,k-1}\ a_{1,k-1}\ a_{-1,k-2}\ a_{0,k-2}\ a_{1,k-2}]^T$ is a column vector of the input sequence $a_{m,k}$, and $\mathbf{y}_k = [y_{k+N} \ldots y_k \ldots y_{k-N}]^T$ is a column vector of a sampler sequence y_k. To minimize (5), we impose a monic constraint to avoid reaching a trivial solution $\mathbf{f} = \mathbf{g} = \mathbf{0}$. Therefore, **f** and **g** are chosen such that

$$E[e_k^2] = \mathbf{f}^T\mathbf{U}\mathbf{f} - 2\mathbf{f}^T\mathbf{T}\mathbf{g} + \mathbf{g}^T\mathbf{R}\mathbf{g} - 2\lambda(\mathbf{I}^T\mathbf{g} - 1), \tag{6}$$

is minimized, where λ is a Lagrange multiplier, $\mathbf{I} = [0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0]^T$, $\mathbf{U} = E[\mathbf{a}_k\mathbf{a}_k^T]$ is a 9×9 autocorrelation matrix of $\mathbf{a}_k$, $\mathbf{R} = E[\mathbf{y}_k\mathbf{y}_k^T]$ is a $(2N+1)\times(2N+1)$ autocorrelation matrix of $\mathbf{y}_k$, and $\mathbf{T} = E[\mathbf{y}_k\mathbf{a}_k^T]$ is a $(2N+1)\times 9$ cross-correlation matrix of $\mathbf{y}_k$ and $\mathbf{a}_k$. The minimization process yields

$$\lambda = 1/(\mathbf{I}^T(\mathbf{U} - \mathbf{T}^T\mathbf{R}^{-1}\mathbf{T})^{-1}\mathbf{I}) \tag{7}$$

$$\mathbf{g} = \lambda(\mathbf{U} - \mathbf{T}^T\mathbf{R}^{-1}\mathbf{T})^{-1}\mathbf{I} \tag{8}$$

$$\mathbf{f} = \mathbf{R}^{-1}\mathbf{T}\mathbf{g} \tag{9}$$

IV. Simulation Result

Consider the BPMR channel in Fig. 1. We define a signal-to-noise ratio (SNR) as $20\log_{10}(1/\sigma)$ in decibel (dB). The 2D 3×3 target and 15-tap 1D equalizer are designed based on a minimum mean-squared error (MMSE) approach [10]. In simulation, each BER is computed based on a minimum number of 500 error bits, and the 2D target and its corresponding 1D equalizer are designed in the presence of media noise and TMR at the SNR required to achieve BER = 10^{-4}.

Furthermore, several targets will be compared in this study. Specifically, we define the system using a 1D target and a conventional (1D) Viterbi detector as "1DTarget"; the system using a zero-corner 2D target and a modified Viterbi detector proposed in [5] as "Zero-corner 2D target"; the system using a cross-track symmetric 2D target (i.e., $G_{-1}(D) = G_1(D)$) and the 2D Viterbi detector (with 36 states and 6 branches) [4] as "Symmetric 2D target"; and the system using the proposed 2D target and the 2D Viterbi detector (with 64 states and 8 branches) [4] as "Asymmetric 2D target."

Fig. 2 compares the performance of different targets at areal densities of 2 and 3 Tbit/in^2 with 0% media noise and 0% TMR, where $T_x = T_z = 18$ nm at 2 Tbit/in^2 and $T_x = T_z = 14.5$ nm at 3 Tbit/in^2, respectively. We found that at 2 Tbit/in^2, "Zero-corner 2D target" performs best, followed by "1D target," and the other 2D targets. The reason that "Symmetric 2D target" and "Asymmetric 2D target" perform worse than "1D target" and "Zero-corner 2D target" might be because the target with a large number of coefficients is more sensitive to disturbances than that with a less number of coefficients. Also, the ITI is not as severe as ISI and AWGN at 2 Tbit/in^2. However, at 3 Tbit/in^2 when ITI is very severe, it is clear that "Symmetric 2D target" and "Asymmetric 2D target" perform better than the others. Therefore, "Symmetric 2D target" and "Asymmetric 2D target" should be employed in the system with severe ITI.

Next, we consider the areal density of 3 Tbit/in^2. Then, we illustrate the performance of different targets at various media noise amounts and 0% TMR in Fig. 3, by plotting the SNR

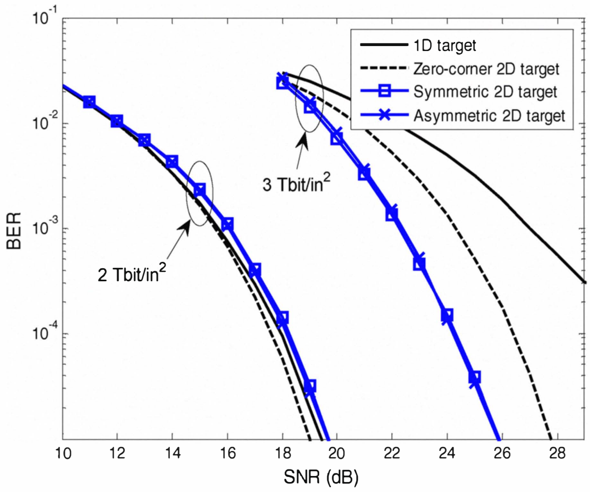

Figure 2. BER performance of different targets with 0% media noise and 0% TMR.

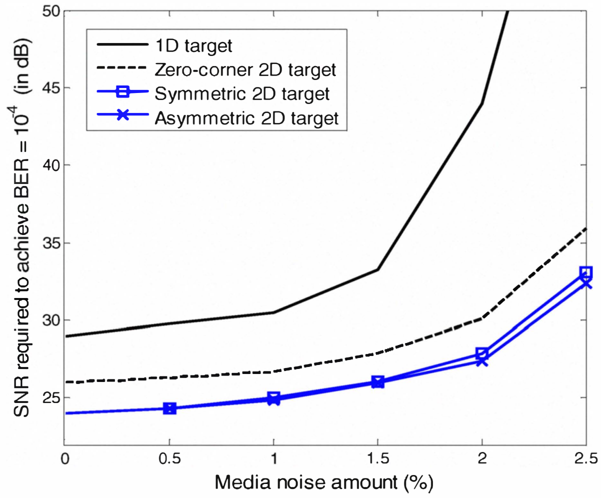

Figure 3. Performance comparison of different media noise amounts with 0% TMR.

required to achieve BER = 10^{-4} as a function of media noise amounts. Apparently, media noise degrades the system performance. In addition, we see that "Asymmetric 2D target" performs best, followed by "Symmetric 2D target" and the other two targets, especially when media noise is high. Again, the reason that "Asymmetric 2D target" yields slightly better performance than "Symmetric 2D target" is because the 2D pulse response in (1) is no longer symmetric in the presence of media noise.

We also compare the performance of different targets with various TMR amounts and 0% media noise in Fig. 4. Similarly, when TMR occurs, it causes the 2D pulse response in (1) to be asymmetric. Hence, it is expected that "Asymmetric 2D target" should perform better than "Symmetric 2D target" as depicted in Fig. 4. Furthermore, when TMR is severe (e.g., greater than 10%), we can see that "Zero-corner 2D target" is also better than "Symmetric 2D target," which might be because the target

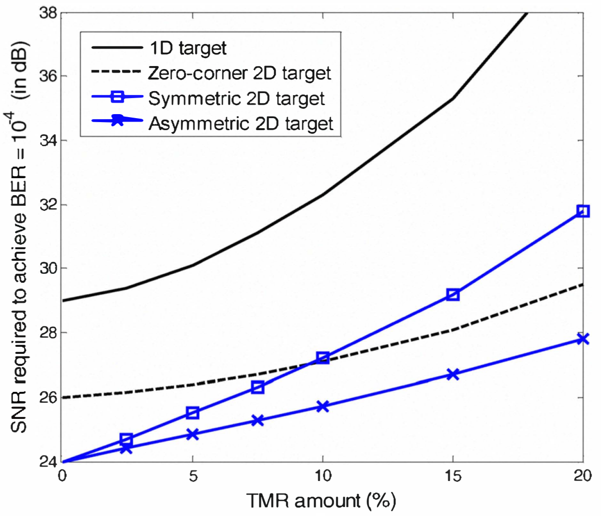

Figure 4. Performance comparison of different TMR amounts with 0% media noise.

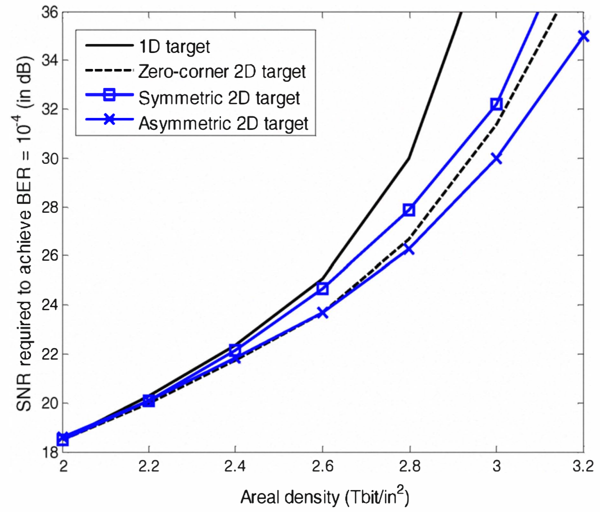

Figure 5. Performance comparison at different areal densities with 2% media noise and 10% TMR.

with a fewer number of coefficients is less sensitive to severe TMR than that with a larger number of coefficients.

Finally, Fig. 5 illustrates the performance comparison of different targets comparison at different areal densities with 2% media noise and 10% TMR. In this case, we found that "Asymmetric 2D target" performs the best if compared to other targets, especially at high areal densities.

V. Conclusion

At high recording densities, bit-patterned media recording systems experience severe ITI, media noise, and TMR. We proposed the design of the 2D cross-track asymmetric target and its corresponding 1D equalizer, based on an MMSE approach, to combat those disturbances. Based on simulations, at low areal densities ($\leq$ 2 Tbit/in^2) when ITI is small, the 1D target can perform sufficiently well if compared to the 2D target. However, at high areal densities (> 2 Tbit/in^2) when ITI is severe, the 2D target must be employed instead of the 1D target. Furthermore, we found that media noise and TMR cause the 2D BPM pulse response to be asymmetric. Thus, in this situation, the BPMR system must utilize the proposed 2D target to obtain the best performance.

However, it should be noted that the proposed 2D target requires the 2D full-complexity Viterbi detector. Consequently, there is a trade-off between performance improvement and increased complexity, when using the proposed 2D target in the BPMR system. Consequently, all advantages gained by the proposed 2D target need to be balanced against the increased implementation cost caused by the 2D full-complexity Viterbi detector.

Acknowledgment

This project is financially supported by a research grant CPN-R&D 01-23-52 EF from I/UCRC in HDD Component, the Faculty of Engineering, Khon Kaen University and National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA), Thailand.

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