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A Study of 2D detection for Two-Dimensional Magnetic Recording

Tanasak Losuwan[1], Chanon Warisarn[1], and Piya Kovintavewat[2]
[1]College of Data Storage Innovation.
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand.
Tel: +668-6997-1001 Fax: +662-329-8362
E-mail: s4690305@kmitl.ac.th, kwchanon@kmitl.ac.th
[2]Data Storage Technology Research Center.
Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand.
Tel: +668-9456-5050, E-mail: piya@npru.ac.th

***Abstract*— Two-dimensional magnetic recording (TDMR) is a recently magnetic recording architecture that can avoid super-paramagnetic phenomenon and can achieve an areal density upto 10 Tb/in^2 by storing one user bit per magnetic grain [1]. In this paper, we propose a two dimensional (2D) multi-track detector for a four-grain TDMR channel model [2, 3] by utilizing the soft information from the detection of the side tracks. Simulation results indicate that at areal density approximately equal to 2.37 Tb/in^2, the proposed scheme provides a significant performance improvement if compared to a conventional scheme, which does not exploit the sidetrack information in decoding process.**

I. Introduction

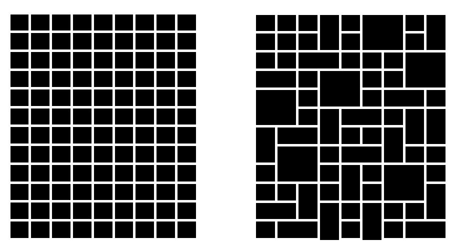
Nowadays, data storage devices are important components and have been used in digital world that grows rapidly in recent years. A magnetic recording or hard disk drive (HDD) is a major choice of data storage devices because it has lower price per storage capacity than other devices. However, in the next few years HDD's areal density will reach its fundamental limit known as *super-paramagnetic*. This phenomenon causes the recorded bits to lose their thermal stability, thus resulting in irretrievable information from those recorded bits. In practically, the areal density of conventional magnetic recording (specifically, perpendicular recording) will be limited around 1 Tb/in^2. Nevertheless, many alternative technologies that can surpass this limitation have been proposed, such as heat-assisted magnetic recording (HAMR) [4], bit-patterned media (BPM) recording [5], and two-dimensional magnetic recording (TDMR) [1].

For HAMR, a near-field laser embedded in the write head so as to heat a tiny spot on a very high coercivity medium before writing a data bit. This technique can reduce the coercivity sufficiently for the head field to change the medium magnetization. Such high coercivity media can be kept stable at smaller grain size, thus supporting smaller data bit and allowing continued areal-density growth. Nonetheless, the way to obtain the media that can maintain the magnetic property during high temperature is still a challenge issue. Furthermore, the method to embed a laser into a head is also a considered issue.

For BPM, each data bit is fabricated in an exactly defined location called an *island*, as opposed to a conventional medium, which has the location of grains randomly. In addition, each data bit is separated from neighboring by non-magnetic material so as to reduce transition noise, thus improving the signal-to-noise ratio (SNR). Clearly, the BPM media experience less noise than conventional media. However, the process to create the medium with uniformly distributed island at very high precision (both in location and shape) is a crucial issue. Although HAMR and BPM can provide more data density, they require novel designs in media and head. To avoid this problem, Wood *et al*. [1] proposed an alternative technology called TDMR, which can achieve the areal density of 10 Tb/in^2.

TDMR tries to achieve this areal density by encoding the user data with very powerful error-correction codes (ECCs) and recording a channel bit into one or a few magnetic grains over the conventional media. The shingled-write with a specially designed "corner writer" has been used for writing process to achieve high areal density. Also, the 2D signal processing and powerful decoding techniques have been employed to overcome errors caused by a severe noise.

Practically, the 2D detection [6-8] has recently been used in many applications. For example, in [7], they used a perfectly equalized channel (without an equalizer) and a modified 2D soft-output Viterbi algorithm (SOVA) to get sidetrack information and exchange soft information with the low-density parity-check (LDPC) decoder. Chang and Cruz [8] employed the 2D detection to recover only the user data on the center-track, but did not address how to simultaneously recovery the user data from adjacent tracks in multi-track recording systems. Moreover, both works were proposed for BPM channels.



(a) (b)

Fig. 1. Media modeling (a) ideal magnetization (b) non-ideal magnetization.

In this paper, we consider the four-grain model of TDMR, and focus on studying the possibility of using the 2D detection to combat both the intersymbol interference (ISI) and the intertrack interference (ITI), which severely occurs in TDMR signal. Specifically, we employ one 2D equalizer and three 2D-SOVA detectors, and exchange the sidetracks' soft information among the three 2D-SOVA detectors.

This paper is organized as follows. After explaining the four-grain channel model in Section II, Section III describes the 2D equalizer and the multi-track detector. Simulation results and discussion are given in Section IV. Finally, Section V concludes this paper.

II. CHANNEL MODELING

A. Method to generate recording media

A four-grain model for TDMR channels has been proposed in [2, 3]. The concept of this model can be expressed as follows. First, imagine the magnetic grain like a plane of tiling that all grains are arrayed in a uniform manner, where the grain size is assumed to be 5.5×5.5 nm^2 per pixel [1], as shown in Fig. 1 (a). Second, make a media granular more realistic by assuming that all magnetic grains are not same size, but they have four possible shapes, namely 1×1, 1×2, 2×1, and 2×2 pixels with the occurrence probability of p_1, p_2, p_3 and p_4, respectively, as displayed in Fig. 2. All magnetic grains distribute randomly over the media corresponding to their probabilities, as illustrated in Fig. 1 (b).

B. Writing modeling

The writing process can be explained as follows. First, let us set one user data bit equal to 3×3 pixels, which means one user bit requires at most nine grains. In case of ideal granular (all grains have same size), the magnetization is shown in Fig. 3 (a), where positive magnetization is black and negative magnetization is white. In general, a uniform magnetization is an effective method, where all grains associated with a given user bit will not span outside that user bit's boundary. On the other hand, in non-ideal magnetization, all grains do not have same size and shape, thus they inevitably span outside the user bit's boundary. Additionally, we assume that the writing sequence of data bits is in the direction from top to bottom and left to right, and the whole grains associated with one user bit will be polarized depending on the polarization of the most bottom-right grain. For example, if the most bottom-right grain fall in positive region, the whole grains will be positive. An example of non-ideal magnetization is displayed in Fig. 3 (b).

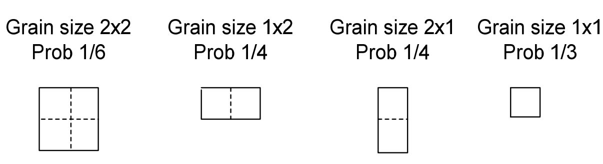


Fig.2. Four possible grain shapes and their probabilities.

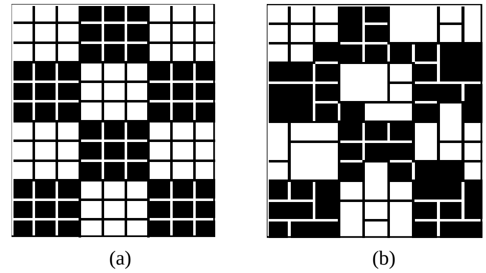


Fig. 3. (a) Ideal magnetization (b) Non-ideal magnetization.

The storage capacity of a four-grain model can be computed as follows. Assuming that the one grain size is 5.5×5.5 nm^2, if the one user bit is 3×3 pixels, one bit cell equal to 3×3×5.5×5.5 = 272.25 nm^2. This areal density can be approximated as 2.37 Tb/in^2. In other cases, if the user bits are 3×4 and 3×5 pixels, the areal density will approximately be 1.77 Tb/in^2, and 1.42 Tb/in^2, respectively.

The readback signal as a function of x (in nm) and y (in nm) coordinates is given by 2D convolution between the magnetization of each pixel point $m(x, y) \in \{\pm 1\}$ and the reader sensitivity function $h(x,y)$ [10]. The readback signal $v(x,y)$ shown in Fig. 4 can be expressed as

$$v(x, y) = \iint m(\xi,\eta)h(x-\xi, y-\eta)d\xi d\eta + n(x, y), \qquad (1)$$

where $n(x, y)$ is additive white Gaussian noise (AWGN). The readback signal $v(x,y)$ is filtered by a seventh-order Butterworth low-pass filter (LPF) and is sampled at time $t = kT$, assuming perfect synchronization at center of the user bit cell. The readout data sequence is assumed to be recovered simultaneously from the readback signals of the three tracks $v_l(x,y)$, where l is the l^{th}-track. The read out data sequence, $r_{k,l}$ is equalized by a 2D equalizer [6]. Finally, the multi-track 2D-SOVA detectors perform sequence detection to determine the most likely input sequence of the center-track.

III. EQUALIZER AND DETECTOR

A. 2D - Equalizer / Target

In conventional recording, a guard band is used between tracks, thus the interference from sidetracks are small and can be negligible. Because TDMR has no guard band, the readback signal experiences severe ITI, which causes a conventional 1D equalizer to perform poorly. Therefore, in this paper, the 2D equalizer [6] is employed in our proposed method in conjunction with the multi-track detector.

B. Multi-Track Detector

The multi-track detector using partial ITI estimated, where soft-information is exchanged between sidetrack and center-track was proposed in [7]. However, we propose the multi-track detector using soft information exchange without partial ITI estimated. Specifically, the sidetracks are detected first, and then the obtained soft information will be used in the

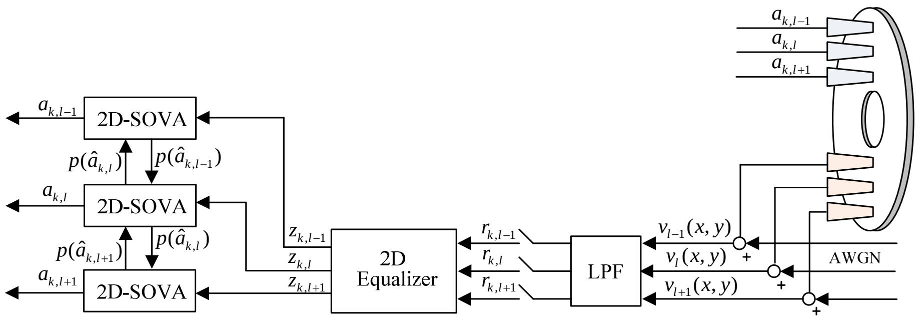


Fig. 4. A TDMR channel model

modified branch metric calculation of the center-track detection. The modified branch metric calculation with exchanged soft information can be described as follows.

Normally, the branch metric is computed from [7]

$$\lambda = (z_{k,l} - d_{k,l})^2 - \log p(\hat{a}_{k,l}), \tag{2}$$

where $z_{k,l}$ is the equalizer output, $d_{k,l}$ is the noiseless channel output, and $\log p(\hat{a}_{k,l})$ is *a priori* probability of data input sequence $a_{k,l}$.

For a multi-track detector, we can apply *a priori* probability from the sidetracks to improve the reliability of the center-track detection by modifying (2) as

$$\begin{aligned}\lambda = &(z_{k,l} - d_{k,l})^2 \\ &-(\log p(\hat{a}_{k,l}) + \log p(\hat{a}_{k,l+1}) + \log p(\hat{a}_{k,l-1})),\end{aligned} \tag{3}$$

where $p(\hat{a}_{k,l+1})$ and $p(\hat{a}_{k,l-1})$ correspond to *a priori* probability of the upper track and the lower track, respectively. The multi-track detectors consist of 2 steps following. At the 1st step all of 2D-SOVA produce log-likelihood ratio (LLR) without *a priori* probability (assumed to be zero). The 2nd step the center SOVA reproduces symbol detection of center track by aiding of *a priori* probability from two sidetracks which is computed from LLR in the first step and also the sidetracks SOVA reproduce symbol detection by using *a priori* probability from center track.

IV. Simulation Results

In our simulation, we compare the performance of several different schemes for areal densities of 1.42, 1.77, and 2.37 Tb/in^2. We utilize the 2D equalizer, which is designed based on the MMSE approach [6]. The equalizer is a 3-by-7 matrix and the target is a 3-by-3 matrix.

The SNR is defined as

$$\text{SNR} = 20\log_{10}(A/\sigma) \tag{4}$$

where A is a saturation level of an isolated pulse [10], and σ is standard deviation of AWGN. Each BER point is computed using as many 4096-bit data sectors as needed to collect 500 error bits, whereas the equalizer taps is designed using only one data sector.

Fig. 5 compares the BER performance of different detections as a function of SNRs, where "Known Sidetracks" denotes the 2D-SOVA assuming the data of sidetrack is known. It is clear from Fig. 5 that when the areal density is low (1.42 Tb/in^2), we observed that no significant performance improvement by using "Multi-track 2D-SOVA" instead of "1D-SOVA, and 2D-SOVA."

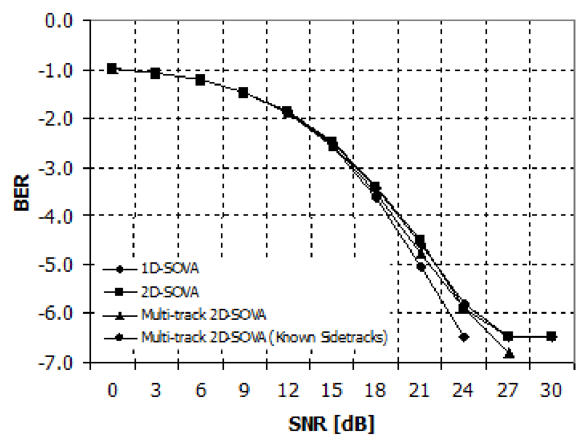


Fig. 5. BER performance of different schemes at 1.42 Tb/in^2

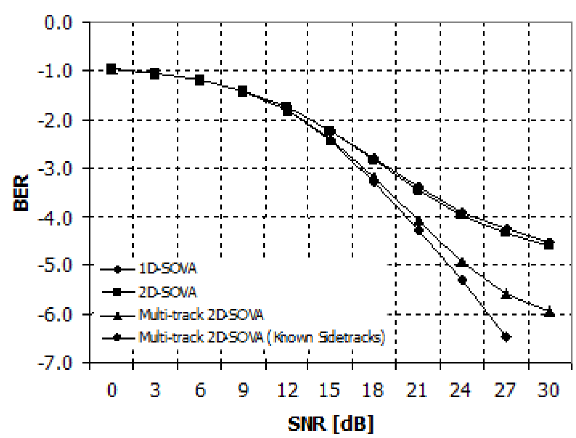


Fig. 6. BER performance of different schemes at 1.77 Tb/in^2

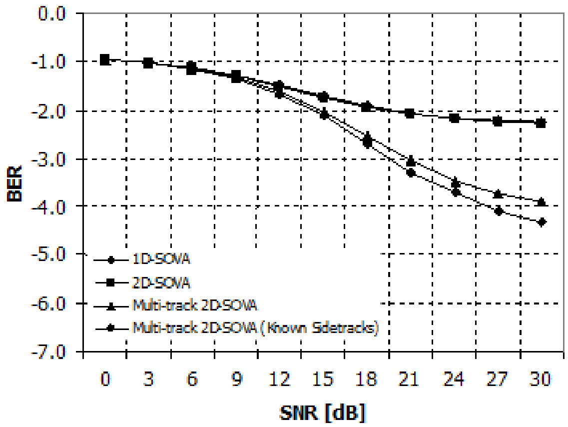


Fig. 7. BER performance of different schemes at 2.37 Tb/in^2

However, when the areal density is moderate (1.77 Tb/in^2) as displayed in Fig. 6, it is evident that the multi-track 2D-SOVA has lower BER than 1D-SOVA, and 2D-SOVA. Specifically, at BER = 10^{-5}, the multi-track 2D-SOVA provides a performance gain of more than 6 dB over the 1D-SOVA and 2D-SOVA without using sidetrack information. We also compare the BER performance of different detection schemes at high areal density (2.37 Tb/in^2) as depicted in Fig. 7. Apparently, similar results are obtained as in low to moderate areal densities. That is, the multi-track 2D-SOVA outperforms both the 1D-SOVA and the 2D-SOVA. Furthermore, it is apparent that the multi-track 2D-SOVA performs close to the multi-track 2D-SOVA with known sidetracks.

V. Conclusion

In this paper, we propose we propose the 2D multi-track detector for a four-grain TDMR channel model, which utilizes the soft information obtained from the sidetrack detection in the branch metric calculation of the center-track detection. Simulation results indicate that the multi-track 2D-SOVA performs better than both the conventional 1D-SOVA and 2D-SOVA, especially when an areal density is high. Clearly, the proposed method is necessary when the system experiences severe ITI and ISI, especially when the areal density is high.

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