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Utilization of multiple read heads for TMR prediction and correction in bit-patterned media recording

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This paper proposes a utilization of multiple read heads to predict and correct a track mis-registration (TMR) in bit-patterned media recording (BPMR) based on the readback signals. We propose to use the signal energy ratio between the upper and lower tracks from multiple read heads to estimate the TMR level. Then, a pair of two-dimensional (2D) target and its corresponding 2D equalizer associated with the estimated TMR will be chosen to correct the TMR in the data detection process. Numerical results show that the proposed system can achieve a very high accuracy of TMR prediction, thus performing better than the conventional system, especially when TMR is severe. [http://dx.doi.org/10.1063/1.4972801]

I. INTRODUCTION

When the center of the read head is not aligned with that of the target track, it causes track mis-registration (TMR) or an off-track situation, which is one of major problems in bit-patterned media recording (BPMR), especially at high areal density (AD). Practically, the TMR can lead to a devastating impact on the data recovery process because of an unequal effect of adjacent tracks on the target track. In general, the servo mechanism can handle the TMR effect; however, it is difficult to control the read head when TMR occurs beyond its limit.[1,2]

In our previous works,[3,4] the TMR mitigation methods were introduced based on the readback signals with a single reader. Specifically, the TMR was predicted by the estimated signal-to-noise ratio (SNR) and the average energy of the readback signal.[3] Thus, the accuracy of the TMR estimation from this method depends mainly on that of the SNR estimation. An iterative method was employed to estimate the TMR level in a coded BPMR system.[4] Although this method is independent of the SNR levels, three detectors are required to perform the TMR estimation. Nonetheless, we found that these methods cannot accurately predict the TMR levels, especially when the system operates in a low TMR regime.

Recently, multiple read heads have been an interesting challenge for next-generation magnetic recording systems, and many researchers utilize a read head array to estimate and mitigate inter-track interference (ITI) in magnetic recording systems.[5–7] Moreover, a practical multi-head multi-track (MHMT) detector[5] that provides a low-complexity approach to adaptively estimate the time-varying ITI was presented. In general, the MHMT detector can handle the ITI effect better than a single-head single-track detector. Thus, the reduced state sequence estimation algorithm[6] to significantly decrease the complexity of the MHMT detector was discussed. G. Mathew[7] et. al., also show the advantages of using multiple read heads in magnetic recording systems. Therefore, this paper proposes to employ multiple read heads to predict and correct the TMR in a BPMR system as illustrated in Fig. 1. Specifically, we first predict a TMR level based on the signal energy ratio between the upper and

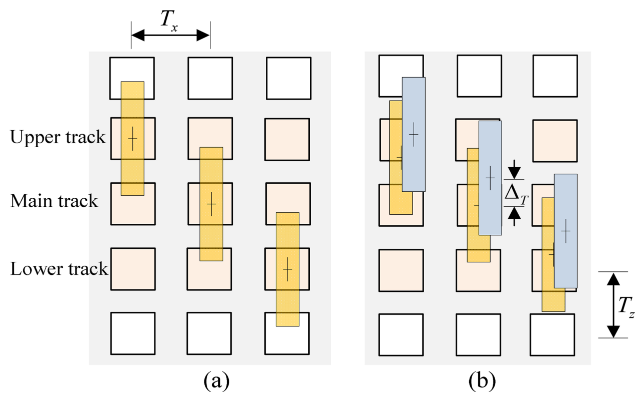

FIG. 1. An array of three read heads for (a) the conventional scheme and (b) the proposed scheme in the BPMR system with TMR, Δ_T.

lower tracks. Then, the estimated TMR level is used to select a pair of two-dimensional (2D) target and its corresponding 2D equalizer from a look-up table that is suitable for the channel with TMR so as to facilitate the data detection process.

The rest of this paper is organized as follows. Section II briefly describes a BPMR channel model, and Section III explains the proposed method. Simulation results are given in Section IV. Finally, Section V concludes this paper.

II. CHANNEL MODEL

Consider a multi-track multi-head BPMR system as shown in Fig. 2. The readback signal, $r_{l,k}$, of the k-th data bit of the l-th track can be expressed as

$$r_{l,k} = \sum\nolimits_n \sum\nolimits_m h_{m,n} x_{l-m,k-n} + n_{l,k}, \tag{1}$$

where $x_{l,k}$'s are the recorded bits, $l \in \{0, -1, +1\}$ represent the main, the upper, and the lower track, respectively, $h_{m,n}$'s are the 2D channel coefficients, m and n represent the time indices of the bit island in the across- and along-track directions, and $n_{l,k}$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ^2. In practice, the channel coefficients, $h_{m,n}$, can be obtained by sampling the 2D Gaussian pulse response at the integer multiples of the track pitch, T_z, and the bit pitch, T_x, according to[4,8]

$$h_{m,n} = A \exp\left\{ -\frac{1}{2c^2} \left[\left(\frac{mT_x}{\mathrm{PW}_x} \right)^2 + \left(\frac{nT_z + \Delta_T}{\mathrm{PW}_z} \right)^2 \right] \right\}, \tag{2}$$

where $A = 1$ is assumed to be the peak amplitude of the pulse response, PW_x is the PW_{50} of the along-track pulse, PW_z is the PW_{50} of the across-track pulse, PW_{50} is the pulse width at half its maximum, $c = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard

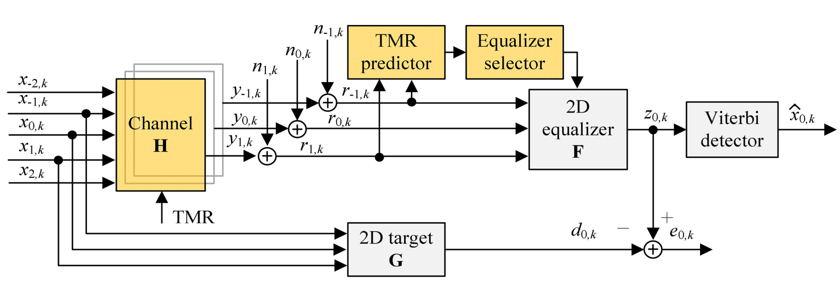

FIG. 2. A multi-track multi-head BPMR channel model with the proposed TMR prediction and correction method.

deviation of a Gaussian, and Δ_T is the head offset as shown in Fig. 1. Here, we define the TMR level as

$$\text{TMR }(\%) = (\Delta_T / T_z) \times 100. \tag{3}$$

At the receiver, the readback signals are read by three read heads and are equalized by a 2D equalizer followed by the 2D Viterbi detector to determine the most likely data sequence on the main track, $\hat{x}_{0,k}$. Note that this paper focuses only on detecting the data on the main track. In addition, each pair of 2D target and 2D equalizer is designed based on a minimum mean-squared error (MMSE) approach[9,10] for each TMR level and is then stored in the look-up table. In a conventional system, each read head will be positioned at the center of each track as shown in Fig. 1(a). In contrast, the proposed scheme employs an array of three read heads, where the upper and lower heads are moved closer to the center head (e.g., by 25% of T_z) as depicted in Fig. 1(b).

III. PROPOSED METHOD

We propose to utilize three read heads to read the data on three adjacent tracks, and process them so as to predict and correct the TMR effect in the BPMR system.

A. TMR predictor

For each TMR level, we compute the energy ratio of the two readback signals associated with the upper and lower tracks (i.e., $r_{-1,k}$ and $r_{1,k}$) according to

$$E_{ratio} = \sum_{k=1}^{S} (r_{-1,k})^2 \Big/ \sum_{k=1}^{S} (r_{1,k})^2, \tag{4}$$

where S is the length of the readback signal samples (i.e., S = 32,768 bits for a 4K-data sector[11]). Next, the estimated TMR level is obtained based on a polynomial least-squares fitting technique, i.e.,

$$\hat{\text{TMR}} = b_0 + b_1 E_{ratio} + b_2 E_{ratio}^2 + \ldots + b_M E_{ratio}^M, \tag{5}$$

where $\hat{\text{TMR}}$ is the estimated TMR, b_i and M are the i^{th} coefficient and a degree of the polynomial equation in (5), respectively, and $i \in \{0, 1, \ldots, M\}$. Then, we perform an extensive simulation search to find a suitable M, where M = 3 provides the best fit between the actual and the estimated TMR levels. Fig. 3(a) plots the estimated TMR level as a function of the energy ratios at 3.0 Tb/in^2. It is apparent that the TMR level can be effectively estimated from (5) based on E_{ratio}.

B. Equalizer selector

The 2D target and its corresponding 2D equalizer are designed for each TMR level based on an MMSE approach, which minimizes a mean-squared error (MSE)[12] according to

$$E\left\{e_{l,k}^2\right\} = E\left\{(z_{l,k} - d_{l,k})^2\right\}, \tag{6}$$

where $E\{\cdot\}$ is the expectation, and $e_{l,k}$ is an error signal between the equalizer output $z_{l,k}$ and the desired signal $d_{l,k}$.

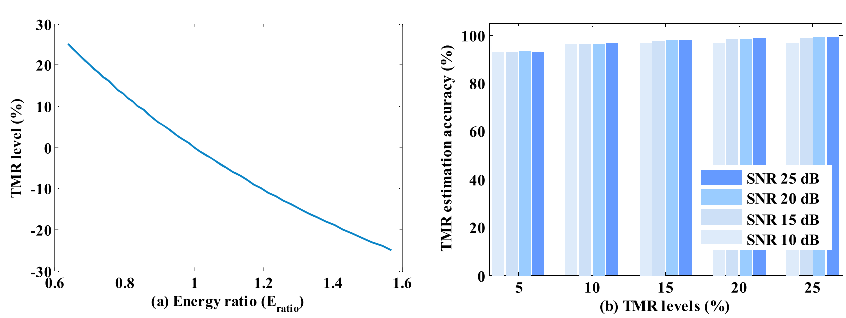

FIG. 3. (a) The relationship between the TMR levels versus the energy ratios and (b) the accuracy of TMR estimation depends the different SNRs, both of them were considered at AD = 3.0 Tb/in^2.

Given the estimated TMR level, the equalizer selector will choose a pair of 2D target and 2D equalizer from the look-up table to alleviate the TMR effect embedded in the readback signal before sending it to the 2D Viterbi detector. Notice that this paper assumes that the 2D target coefficients are the 2D channel coefficients when the system has 0% TMR, similar to previous work.[4] Hence, we fix this 2D target and use it to design all 2D equalizers for each TMR level i.e., at -25%, -20%, ..., -5%, 0% 5%, ..., and 25%, based on the MMSE approach, which will be all stored in the look-up table.

IV. RESULTS AND DISCUSSION

We evaluate the system performance at the AD of 3.0 Tb/in^2 (i.e., $T_x = T_z = 14.5$ nm) among 1) the conventional system I without TMR prediction and correction method; 2) the conventional system II, assuming that TMR is known and the receiver uses the 2D equalizer designed for that TMR; and 3) the proposed system, where the 2D Gaussian pulse response with the along-track PW_{50} of 19.4 nm and the across-track PW_{50} of 24.8 nm is considered, similar to previous work.[4] In simulation, the SNR is defined as

$$\mathrm{SNR} = 20\log_{10}(1/\sigma) \text{ in decibel (dB)}, \tag{7}$$

where σ is a standard deviation of AWGN. We also measure the accuracy of TMR estimation by

$$\text{accuracy } (\%) = 100 - \frac{\left|\hat{\mathrm{TMR}} - \mathrm{TMR}\right|}{\mathrm{TMR}} \times 100, \tag{8}$$

where $\hat{\mathrm{TMR}}$ is the estimated TMR obtained from the proposed method, and TMR is the actual TMR embedded in the readback signal. Fig. 3(b) shows the accuracy of TMR estimation in percentage at different SNRs. Clearly, the proposed method can predict the TMR well, especially at high TMR levels. In addition, we found that the accuracy of our TMR estimation method is independent of SNRs.

From now on, we assume that the BPMR system experiences the TMR effect only in the upward direction (i.e., Δ_T is a positive value). Note that this paper will not consider a media noise in the system so as to make it easy to understand the behavior of the TMR effect. Fig. 4(a) compares the performance of different systems at AD = 3.0 Tb/in^2 in terms of the MSE in dB according to

$$\mathrm{MSE} = 10\log_{10}\left(\sum_{k=1}^{S}\{z_{0,k} - d_{0,k}\}^2\right). \tag{9}$$

Apparently, the proposed system yields the lowest MSE for all TMR levels. That means the proposed equalizer can perform with the proposed multi-track reading systems.

Finally, Fig. 4(b) compares the performance of different systems at AD = 3.0 Tb/in^2 by plotting the SNR required to achieve bit-error rate (BER) of 10^{-4} as a function of TMR levels. It is clear that the proposed system is superior to other systems, especially when TMR is large. The reason might be because the proposed TMR estimation method can achieve a very high accuracy for all TMR levels as depicted in Fig. 3(b). Therefore, it can be implied that the proposed method can help improve the quality of the readback signal before sending it to the 2D Viterbi detector, thus leading to a better

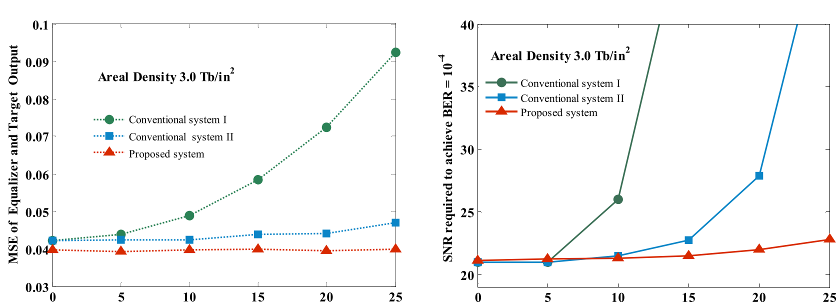

FIG. 4. (a) MSE and (b) BER performance comparison of different systems at AD of 3.0 Tb/in^2.

BER performance. It can be concluded that by moving the upper and lower read heads closer to the center read head as shown in Fig. 1(b), one can obtain the better readback signals with less ITI effect if compared to the conventional setting in Fig. 1(a), thus leading to the improved system performance.

V. CONCLUSION

This paper proposes the TMR prediction and correction method for a multi-track multi-head BPMR system. The energy ratio between the readback signals of the upper and lower tracks is used to predict the TMR level. Then, the TMR effect is corrected by using the 2D target and its corresponding 2D equalizer that are the best suit for the estimated TMR level. Simulation results indicate that the proposed system can effectively estimate the TMR level, thus performing better than the conventional systems, especially when the TMR is severe.

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[1] L. N. He *et al.*, IEEE Trans. Magn. **34**, 2348 (1998).
[2] Y. Chang, D. Park, N. Park, and Y. Park, IEEE Trans. Magn. **38**, 1441 (2002).
[3] W. Busyatras, C. Warisarn, L. M. M. Myint, and P. Kovintavewat, IEICE Trans. Electron. **E98-C**, 892 (2015).
[4] W. Busyatras, C. Warisarn, L. M. M. Myint, P. Supnithi, and P. Kovintavewat, IEEE Trans. Magn. **51**, 3002104 (2015).
[5] B. Fan, H. K. Thapar, and P. H. Siegel, IEEE Int. Conf. on Commun. (ICC), 425 (2015).
[6] B. Fan, H. K. Thapar, and P. H. Siegel, IEEE Trans. Magn. **51**, 3001404 (2015).
[7] G. Mathew, E. Hwang, J. Park, G. Garfunkel, and D. Hu, IEEE Trans. Magn. **50**, 3300907 (2014).
[8] S. Nabavi, Ph.D. dissertation, Dept. Elect. Eng., Carnegie Mellon Univ., Pittsburgh, PA, USA, 2008.
[9] J. Moon and W. Zeng, IEEE Trans. Magn. **31**, 1083 (1995).
[10] Y. Ng *et al.*, IEEE Trans. Magn. **48**, 1976 (2012).
[11] HGST a Western Digital company, HGST. Inc., 1 (2014).
[12] S. Karakulak, P. H. Siegel, J. K. Wolf, and H. N. Bertram, IEEE Trans. Magn. **46**, 3639 (2010).