The 29th International Technical Conference on Circuit/Systems Computers and Communications (ITC-CSCC), Phuket, Thailand, July 1-4, 2014

Estimating Track Mis-Registration Based on Readback Signal in Bit-Patterned Media Recording Systems

Wiparat Busyatras*, Autthasith Arrayangkool*, Chanon Warisarn*,
Lin M. M. Myint†, Pornchai Supnithi*‡, and Piya Kovintavewat§
*College of Data Storage Innovation, ‡Telecommunications Engineering Department,
King Mongkut's Institute of Technology Ladkrabang 10520, Thailand.
Email: s5690155@kmitl.ac.th, s4690151@kmitl.ac.th, kwchanon@kmitl.ac.th
†School of Information Technology, Shinawatra University, Pathumthani 12160, Thailand.
§Data Storage Technology Research Center, Nakhon Pathom Rajabhat University Nakhonpathom 73000, Thailand.

***Abstract*—Track mis-registration (TMR) is one of crucial factors on the performance of bit-patterned media recording (BPMR) systems. Because of the movement of a read head and the rotation of a magnetic disk, the center of the read head may move away from its center location of a data track, thus resulting in a TMR effect, which can deteriorate the overall system performance. In general, the TMR effect can be detected and handled by a servo system. However, the servo system usually requires inherent sector-level latency mechanisms for head adjustment. Therefore, this paper proposes a method to estimate a TMR amount based only on a readback signal. Firstly, the signal-to-noise ratio (SNR) is estimated based on the peak amplitude of the readback signal. Then, we determine a TMR level using the average signal energy and the estimated SNR. Simulation results show that the proposed method can predict the TMR level embedded in the readback signal with 95% accuracy, especially when TMR and SNR level are high.**

Keywords*—Bit-patterned media recording (BPMR); estimation method; signal-to-noise ratio (SNR); track mis-registration (TMR)

I. Introduction

Track mis-registration (TMR) effect is a major obstacle for increasing an areal density (AD) in ultra-high density magnetic recording systems such as bit-patterned media recording (BPMR) [1], [2]. The TMR effect is occurred due to the misalignment between the center of the read head and that of the main data track as illustrated in Fig. 1. Because of TMR, the readback signal may experience even more severe inter-track interference, which will further degrade the performance of data recovery process in BPMR systems [3], [4].

To handle the TMR effect, a servo system provides an inherent sector-level latency of the detection of servo bursts before any head adjustment can be made. This servo burst field has the information that can be used to estimate the amount of read head offset. However, it is generally difficult to predict the TMR quantity to the next servo sector, when TMR is compensated by only burst signals, especially when TMR goes beyond the limit [5], [6], [7].

In practice, several TMR estimation methods based on the readback signal have been proposed in the literature [8], [9]. Nonetheless, these methods require the knowledge of some recorded data and employ high complexity processing (e.g., calculating many correlation functions) for estimating TMR levels. Thus, this paper proposes a novel TMR estimation method, which is based only on the readback signal. Specifically, at high SNR, our method can provide up to 95% accuracy at high TMR level (i.e., 20%-25%).

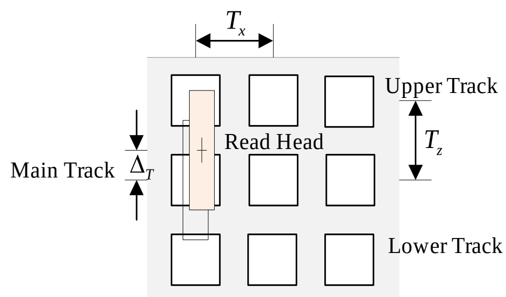

Fig. 1. TMR in a BPMR system, i.e.,Δ_T.

This work begins with studying the relationship among the statistical information of the readback signal, signal-to-noise ratios (SNRs), and various TMR levels. Hence, these relationships will be employed to generate the mathematical equations to use estimating the SNR and the TMR level. In this work, we first estimate the SNR using the peak amplitude of the readback signal from one data sector. Then, this estimated SNR level will be utilized to estimate the TMR level according to the readback signal energy.

This paper is organized as follows. In Section II, the BPMR channel model is described. Section III explains the proposed TMR estimation method. The simulation results are given in Section IV. Finally, Section V concludes this paper.

II. Channel Model

In this paper, we focus on a discrete BPMR channel model [5], [6] as depicted in Fig. 2. The readback signal of the k^{th} data bit on the main track can be expressed as

$$r_{0,k} = \sum_n \sum_m h_{-m,n} x_{-m,k-n} + n_{0,k}, \tag{1}$$

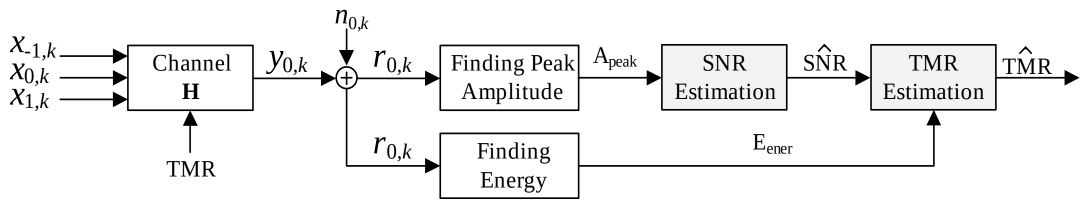

Fig. 2. Block diagram of BPMR system with proposed SNR and TMR estimations.

where $x_{0,k}$'s are the recorded bits on the main track, $h_{m,n}$'s are the 2D channel coefficients, *m* and *n* represent the time indices of the bit island in the across-track and the along-track directions, and $n_{0,k}$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ^2. Practically, the channel response coefficients $h_{m,n}$ of BPMR systems can be generated by sampling the 2D Gaussian pulse response at the integer multiples of the bit period, T_x, and the track period, T_z, i.e.,

$$h_{m,n} = P\left(nT_z + \Delta_T, mT_x\right), \tag{2}$$

where $P(z,x)$ is the 2D Gaussian pulse response, *z* and *x* are the time indices in the across-track and the along-track directions, $\{m,n\} \in (-L,...,0,...,L)$, 2*L*+1 is the length of $P(z,x)$, 2*L*+1 is the 2D channel length, *L* is an integer, and Δ_T is the head offset or the distance between the center head and the center of the main track as shown in Fig. 1. Generally, *L* should be large enough to ensure that the tail amplitude of $P(z,x)$ is small (here, we use *L* = 1 for simplicity). In this paper, the sign of Δ_T is assumed to be positive for the upward offset, where the TMR level is defined as

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

Furthermore, we consider the 2D Gaussian pulse response of the form [10]

$$P\left(z,x\right) = A\exp\left\{-\frac{1}{2c^2}\left[\left(\frac{x}{\text{PW}_x}\right)^2 + \left(\frac{z+\Delta_T}{\text{PW}_z}\right)^2\right]\right\}, \tag{4}$$

where *A* = 1 is assumed to be the peak amplitude of the pulse response, $\text{PW}x$ is the PW_{50} of the along-track pulse, $\text{PW}z$ 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 deviation of a Gaussian.

In Fig. 2, the recorded bits, $x_{-1,k}, x_{0,k}$, and $x_{1,k}$ from the upper, the main, and the lower tracks, respectively, are sent to the BPMR channel corrupted by TMR and AWGN. At the read side, the readback signal is used to determine its peak amplitude, A_{peak}, and the average energy, E_{ener}, simultaneously. Then, the estimated SNR, $\hat{\text{SNR}}$, is obtained based on A_{peak} (will be explained in Section III. A). Finally, we compute the estimated TMR, $\hat{\text{TMR}}$, using E_{ener} and $\hat{\text{SNR}}$.

III. Proposed Method

A. SNR Estimation

In this work, we collect 100 samples of the readback signals at each SNR level from 0 to 25 decibel (dB), where each readback signal is affected by a random TMR level from 0% to 25%. For each SNR level, we average the peak amplitude of all readback signals. Using these two data sets of the SNRs and the average peak amplitudes, we propose to employ a curve fitting technique to obtain a polynomial function to approximate the SNR based on the known average peak amplitude. The polynomial function using the curve fitting technique is

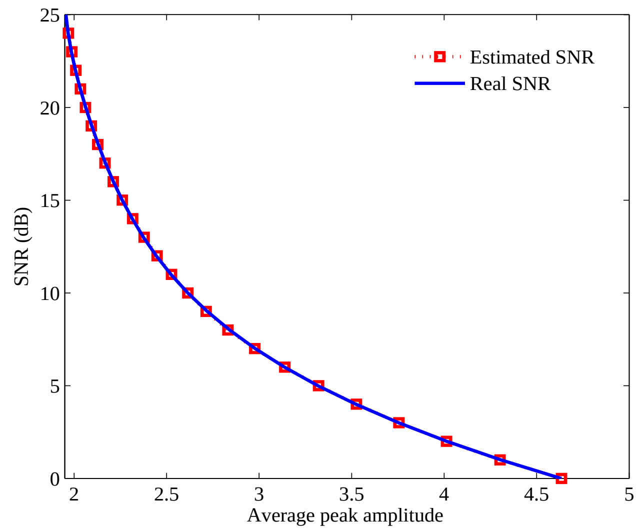

Fig. 3. The relationship between the SNR levels and the average peak amplitude of the readback signals.

$$\hat{\text{SNR}} = a_0 + a_1 y + a_2 y^2 + \ldots + a_N y^N, \tag{5}$$

where $\hat{\text{SNR}}$ is an estimated SNR, a_i is the i^{th} coefficient of the polynomial equation, $i \in \{0, 1, \ldots, N\}$, *N* is a degree of the polynomial equation, *y* is the peak amplitude of the readback signal. Based on extensive heuristic research, we found that *N* = 5 is sufficient for our model because a higher order does not provide any performance gain on the accuracy of SNR estimation. In Fig. 3, we compare the real SNR value and the estimated SNR using (5). The x-axis is the average peak amplitude of the readback signals and the y-axis is the SNR levels. The result is similar so that we use the curve fitting for estimated SNR level.

B. TMR Estimation

To estimate the TMR level, we compute the energy of the readback signal at SNR = 0 dB for each TMR level (i.e., 0, 5,

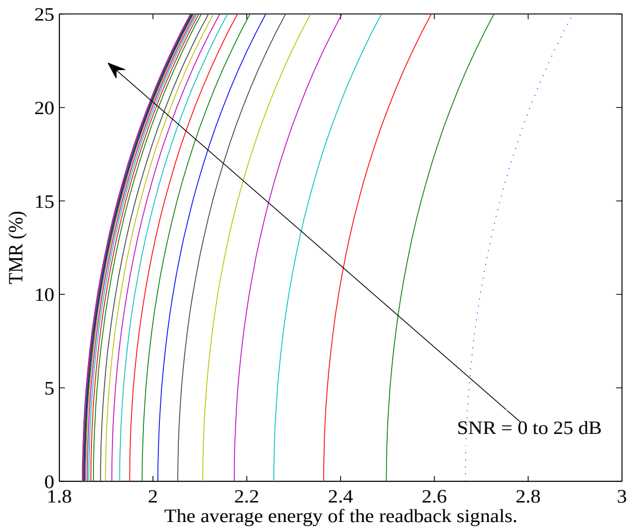

Fig. 4. The relationship between the TMR (%) levels and the average energy of the readback signals.

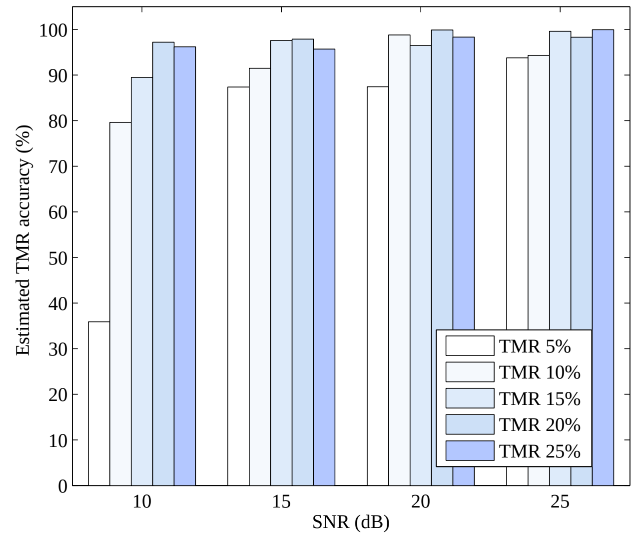

Fig. 5. The relationship between the SNR levels and the percentage of the estimation accuracy of the proposed method.

10, 15, 20, and 25%) according to

$$\mathrm{E_{ener}} = \frac{1}{M} \sum_{k=1}^{M} r_{0,k}^2, \tag{6}$$

where M is the length of the readback signal, which is equal to 32768 bits as a 4k data sectors [11].

Next, we also use the curve fitting technique so as to obtain a polynomial function that provides the best fit line for the relation between the TMR and the average energy of all readback signals. This polynomial function can be utilized to approximate the TMR level according to

$$\hat{\mathrm{TMR}} = b_0 + b_1 u + b_2 u^2 + \ldots + b_F u^F, \tag{7}$$

where $\hat{\mathrm{TMR}}$ is an estimated TMR, b_i is the i^{th} coefficient of the polynomial equation, $i \in \{0, 1, \ldots, F\}$, F is a degree of the polynomial equation (here we use $F = 5$ for simplicity), u is the average signal energy, which is equal to $\mathrm{E_{ener}}$ in Fig. 2.

Fig. 4 depicts the relationship between the TMR level and the average energy by plotting the average energy of all readback signals as a function of TMR levels. We repeat this step by varying the SNR level from 0 to 25 dB to obtain each curve in Fig. 4. The line dot is the SNR 0 dB and the next lines are the SNR level to increase by 1 dB up to SNR 25 dB. It is apparent that if we know the estimated SNR ($\hat{\mathrm{SNR}}$) and the average energy ($\mathrm{E_{ener}}$), we can easily compute the estimated TMR ($\hat{\mathrm{TMR}}$) from (7).

IV. Simulation Results

We test the proposed method in the BPMR system given in Fig. 2 at an areal density (AD) of 2 Tb/in^2, where both the bit period and the track pitch are $T_x = T_z = 18$ nm, the along-track PW_{50} is 19.4 nm, and the across-track PW_{50} is 24.8 nm, as similar to [12]. The SNR is defined as

$$\mathrm{SNR} = 20\log_{10}\left(\frac{1}{\sigma}\right) \quad (\text{in dB}), \tag{8}$$

where σ is a standard deviation of AWGN.

The performance of the proposed method is measured by the accuracy, which is defined as

$$\text{accuracy}(\%) = 100 - \frac{\left|\hat{\mathrm{TMR}} - \mathrm{TMR}\right|}{\mathrm{TMR}} \times 100, \tag{9}$$

where $\hat{\mathrm{TMR}}$ is the estimated TMR, which is obtained from the proposed method, and TMR is the actual TMR level embedded in the readback signal.

Fig. 5 demonstrates the percentage of the estimation accuracy of the proposed method in the BPMR system. Clearly, the proposed method can provide an accuracy of more than 80% when the TMR level is greater than 10%. In addition, the accuracy percentage approaches to nearly 100% when SNR is very high. For example, at high SNR (e.g., 20 dB and 25 dB) of each TMR level (from 5% to 25%), we can achieve the accuracy of about 95%. Consequently, the proposed estimation method can be effectively employed to estimate the TMR level, especially when SNR and TMR are high. However, the low SNR levels provide an accuracy of less than 40%, in particularly, when the TMR level is low because the effect of TMR is dominant by high AWGN noise. Therefore, the accuracy of the proposed method is not well.

V. Conclusion

This paper proposes the TMR estimation method by using only the readback signal for a BPMR system corrupted by AWGN and, inter-symbol interference and inter-track interference. Specifically, we first estimate the SNR based on the peak amplitude of the readback signal. Then, the estimated TMR level is determined based on the readback signal energy and the estimated SNR level. Experiment results indicate that the proposed method can effectively estimate the TMR level, especially when SNR and TMR are large. It should be pointed out that this estimation method can be adapted in designing a two-dimensional (2D) equalizer and a 2D detector in BPMR systems so as to cope with this TMR problem.

ACKNOWLEDGMENT

This work was supported by College of Data Storage Innovation (D*STAR), King Mongkut's Institute of Technology Ladkrabang Research Fund, and Nakhon Pathom Rajabhat University, Thailand.

REFERENCES

[1] P. W. Nutter, I. T. Ntokas, B. K. Middleton, and D. T. Wilton, W. Chang and J. R. Cruz, "Effect of island distribution on error rate performance in patterned media," *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 3214–3216, Oct. 2005.

[2] Z. Jin, N. Bertram, B. Wilson, and R. Wood, "Simulation of the offtrack capability of a one terabit per square inch recording system,"*IEEE Trans. Magn.*, vol. 38, no. 2, pp. 1429–1435, Mar. 2002.

[3] S. Nabavi, B. V. K. V. Kumar, and J. Bain, "Mitigating the effects of track mis-registration in bit-patterned media," in *Proc. IEEE Int. Conf. Commun.*, pp. 1061–2065, May 2008.

[4] S. Nabavi, B. V. K. Vijaya Kumar and J. Zhu, "Modifying Viterbi algorithm to mitigate inter-track interference in bit-patterned media,"*IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2274–2276, Jun. 2007.

[5] Y. Chang, D. Park, N. Park, and Y. Park, "Prediction of track misregistration due to disk flutter in hard disk drive," *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 1441–1446, Mar. 2002.

[6] R. Ehrlich and D. Curran, "Major HDD TMR sources and projected scaling with TPI," *IEEE Trans. Magn.*, vol. 35, pp. 885–891, Mar. 1999.

[7] J. S. McAllister, "Characterization of disk vibrations on aluminum and alternate substrates," *IEEE Trans. Magn.*, vol. 33, pp. 968–973, Jan. 1997.

[8] B. G. Roh, S. U. Lee, J. Moon, and Y. Chen, "Single-head/Single-track detection interfering tracks," *IEEE Trans. Magn.*, vol. 38, no. 4, pp. 830–838, Jul. 2002.

[9] L. M. M. Myint and P. Supnithi, "Off-track detection based on the readback signals in magnetic recording," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 4590–4593, Nov. 2012.

[10] S. Nabavi, *Signal processing for bit-patterned media channels with inter-track interference*. Ph.D thesis, Carnegie Mellon University, Pittsburgh, Dec. 2008.

[11] HGST a Western Digital company, "Advanced Format Technology Brief," *HGST. Inc*., pp. 1–4 , Mar. 2014.

[12] A. Arrayangkool, C. Warisarn, and P. Kovintavewat, "A recorded-bit patterning scheme with accumulated weight decision for bit-patterned media recording," *IEICE Trans. Electron.*, vol. E96-C, no. 12, pp. 1490–1496, Dec. 2013.