Mitigation of TMR Using Energy Ratio and Bit-Flipping Techniques in Multitrack Multihead BPMR Systems

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Track misregistration (TMR) in ultra-high density bit-patterned media recording (BPMR) is one of the crucial problems, because it can severely degrade the overall system performance. In practical, TMR can be detected and adjusted by a servo control loop system. However, this paper proposes to utilize multiple readback signals obtained from the optimized positioning of the two side read head closer to the main read head to improve the TMR prediction process in a multitrack multi-head BPMR system with position jitter noise. In addition, we also propose the soft-information exchange and the bit-flipping techniques for the multitrack data detection, so as to improve the bit-error rate (BER) performance of all three data tracks simultaneously. Simulation results indicate that the proposed system is superior to the conventional system, especially, when the amount of TMR and position jitter is high. Furthermore, we also found that the upper and lower read heads, which are moved closer to the center track by 25% of a track pitch, will provide the best BER performance with and without position jitter noise.

***Index Terms*—Bit-patterned media recording (BPMR), multitrack multihead, soft-information exchange, track misregistration.**

I. INTRODUCTION

IN BIT-PATTERNED media recording (BPMR) aimed at magnetic recording densities of 1 terabit per square inch (Tb/in^2) and higher [1]–[5], adjacent tracks may become very close leading to significant track misregistration (TMR), which can further degrade the performance of the system. In practice, the servo mechanism with the expense of an inherent sector-level latency of detection of servo bursts can handle the TMR effect; however, it is difficult to control the read head when TMR occurs beyond its limit [1], [6].

In our previous works [3], [4], the TMR mitigation methods were presented based on the readback signals with a single reader. Specifically, the TMR is predicted by the estimated signal-to-noise ratio (SNR) and the average energy of the readback signal; however, the TMR estimation accuracy depends mainly on the estimated SNR. To improve its performance, we introduced an iterative TMR mitigation method for a coded BPMR system [4], whose TMR estimation is independent of SNR prediction. Nonetheless, this method still cannot accurately estimate a TMR level when TMR is small.

To solve this problem, we proposed to employ multiple read heads [7]–[9] to subside the TMR effect as shown in Fig. 1(a), which can perform better than a conventional single reader system as explored in [5]. Although this method utilizes three read heads, where the upper and lower read heads are moved closer to the center track, as shown in Fig. 1(b), to read three data tracks simultaneously, but only the data from the center track is recovered. Therefore, to estimate the three data tracks jointly and effectively, we propose a TMR mitigation method with three-track data detection for a multitrack multihead BPMR system with position jitter noise. In addition, we also investigate the optimal position of the read heads to offer a high TMR prediction accuracy and provide a good system performance. Simulation results show that the proposed system can achieve a very high accuracy of TMR prediction, thus performing better than the conventional system, especially, when the TMR level and the position jitter are high.

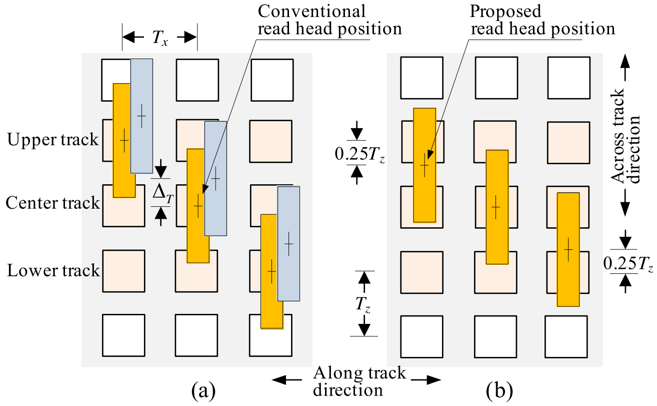

Fig. 1. Schematics of the array read head positions in the BPMR system for: (a) conventional scheme with TMR, Δ_T; and (b) proposed scheme where the upper and lower read heads are moved closer to the center read head by 25% of a track pitch.

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. BPMR CHANNEL MODEL

Consider a discrete-time BPMR channel model as shown in Fig. 2. The readback signal of the kth data bit of the

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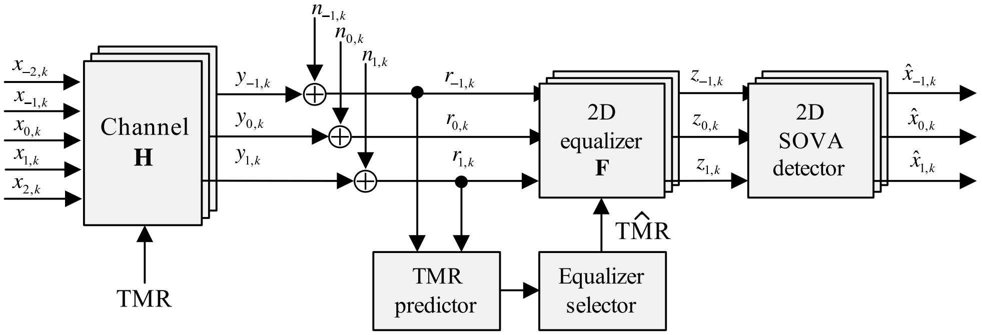


Fig. 2. Multitrack multihead BPMR channel model together with the proposed TMR mitigation method with three-track data detection.

lth track can be expressed as

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

where $x_{l,k}$'s are the recorded bits, $l \in \{0, -1, +1\}$ denotes the center, upper, and lower track, respectively, 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 2-D Gaussian pulse response at the integer multiples of a track pitch, T_z, and a bit pitch, T_x, according to [10]

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

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 pulsewidth 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, Δ_x is the along-track location fluctuation (or position jitter [11]), Δ_z is the across-track location fluctuation, and Δ_T is the head offset as shown in Fig. 1(a). Here, we assume that Δ_x and Δ_z are modeled as a truncated Gaussian probability distribution function with zero mean and variance σ_j^2, where σ_j is specified as the percentage of T_x. In this paper, a TMR level is defined in percentage as

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

At the receiver, the three readback signals $\{r_{-1,k}, r_{0,k}, r_{1,k}\}$ are obtained simultaneously by using an array of three read heads, where the upper and lower heads are moved closer to the center head by $0.25T_z$. Then, these readback signals will be equalized by the 2-D equalizers followed by the 2-D-SOVA detectors [12] to produce the estimated three data tracks.

III. PROPOSED SYSTEM

This section presents the TMR prediction method based on the readback signals and the three-track data detection scheme based on the soft-information exchange and bit-flipping techniques.

A. TMR Prediction

To predict the TMR level, we compute the energy ratio, E_{enr}, from the readback signals according to

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

where $r_{-1,k}$ and $r_{1,k}$ are the readback signals of the upper and lower tracks, respectively, and S is the length of the readback signal samples, i.e., $S = 32\,768$ b for a 4K-data sector [13]. Note that these readback signals are obtained from the read heads that are moved closer to the center track as shown in Fig. 1(b). Although moving the two side read heads closer to the main track will increase the amount of interference, our proposed bit-flipping techniques will correct for this. An extensive investigation comparing energy ratio against TMR levels has shown that an offset of the side heads by 25% of the track pitch closer to the main read head offers optimal BER performance and TMR prediction accuracy.

In addition, to confirm that the energy ratio can be used to predict the TMR level, we consider the system at the areal density (AD) of 3 Tb/in^2, when it was corrupted by media noise (e.g., position jitter). This paper assumes that the position jitter amount (σ_j / T_x) are 0%, 3%, 5%, and 10%, respectively, and SNR is fixed at 20 decibel (dB). As shown in Fig. 3, we can see that the relationship between the TMR level and the energy ratio has the same trend for all position jitter amounts. Thus, we can employ only one polynomial equation to estimate the TMR level when the TMR does not exceed ±15%. Specifically, the estimated TMR level, $T\hat{M}R$, is obtained based on a least-squares fitting technique according to

$$\hat{\mathrm{TMR}} = b_0 + b_1 E_{\mathrm{enr}} + b_2 E_{\mathrm{enr}}^2 + \cdots + b_\upsilon E_{\mathrm{enr}}^\upsilon \tag{5}$$

where b_i and υ are the ith coefficient and a degree of the polynomial equation in (5), respectively. From our extensive simulation, we found that υ equals to 3 provides the best fit between the actual and the estimated TMR levels.

In this paper, we also assume that the 2-D target coefficients are the 2-D channel coefficients when the channel has 0% TMR, as used in [5]. Hence, we fix this 2-D target and design a 2-D equalizer for each TMR level based on a minimum mean-squared error approach [12], [14], which will be stored in the lookup table. Given an estimated TMR level, the equalizer

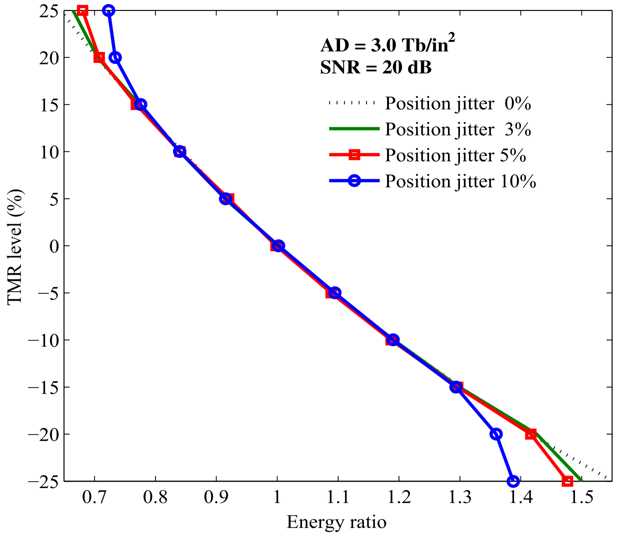


Fig. 3. Relationship between the TMR level and the energy ratio for different position jitter amounts at AD $= 3$ Tb/in^2 and SNR $= 20$ dB.

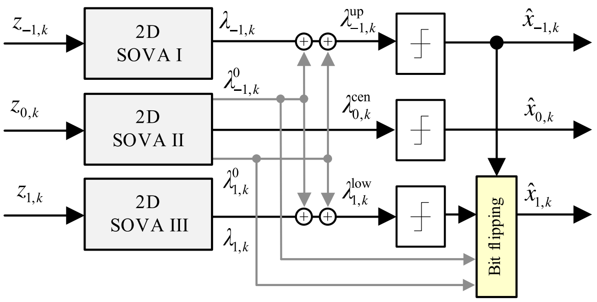


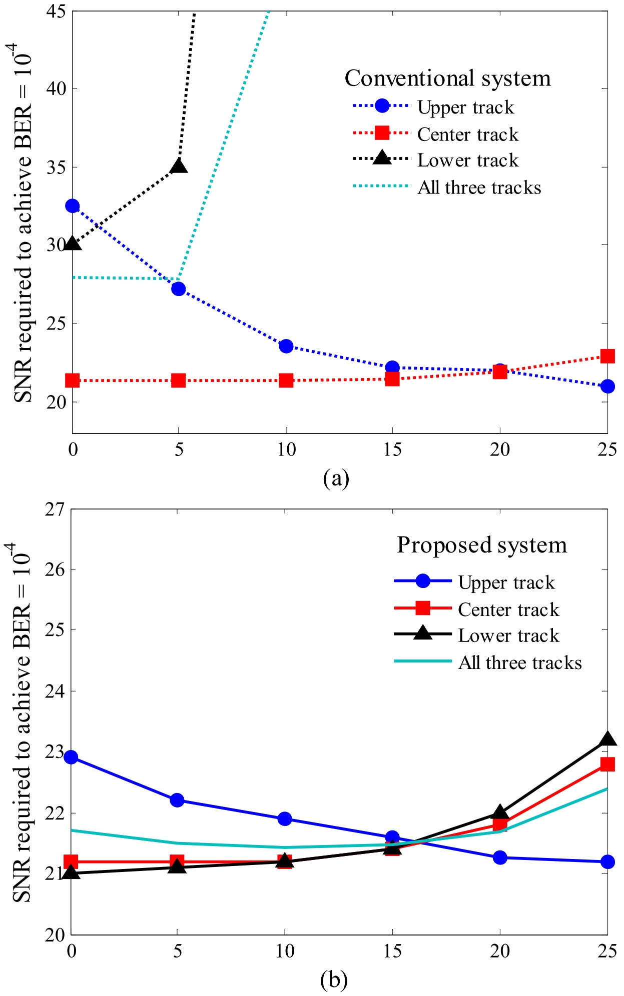
Fig. 4. Soft-information exchange and bit-flipping techniques for three-track data detection when TMR is assumed to be positive (upward offset).

selector will choose a pair of 2-D target and 2-D equalizer from the lookup table to combat the TMR-affected readback signal, as shown in Fig. 2.

B. Three-Track Data Detection

For the proposed three-track data detection, the equalized signals $\{z_{-1,k}, z_{0,k}, z_{1,k}\}$ are processed by three 2-D SOVA detectors separately to produce the log-likelihood ratio (LLR) sequences for three tracks, i.e., $\lambda_{-1,k}$, $\lambda_{0,k}$, and $\lambda_{1,k}$, before making a hard decision, as demonstrated in Fig. 4. Among three detectors, the center detector is designed to generate the LLR of the center track, $\lambda_{0,k}$, as well as that of its sidetracks, i.e., $\lambda^0_{-1,k}$ and $\lambda^0_{1,k}$. Since the upper and lower read heads are located close to the center track, the sidetrack LLRs from the center detector will be used to improve the quality of the LLRs of the upper and lower tracks. In particular, the LLR of the upper track is adjusted by $\lambda^{\mathrm{up}}_{-1,k} = \lambda_{-1,k} + (\lambda^0_{-1,k} + \lambda^0_{1,k})$, whereas that of the lower track is given by $\lambda^{\mathrm{low}}_{1,k} = \lambda_{1,k} + (\lambda^0_{-1,k} + \lambda^0_{1,k})$. Note that each detector employs a trellis with 64 states and 8 incoming and outgoing branches at each state, considered a symbol with three bits from three adjacent tracks.

Moreover, we also propose a bit correcting system, in which, the output bits of the lower track, $\hat{x}_{1,k}$, is decided based on the sign of $\lambda^0_{-1,k}$ and $\lambda^0_{1,k}$ because $\hat{x}_{-1,k}$ and $\hat{x}_{1,k}$ are reflected to the sign of $\lambda^0_{-1,k}$ and $\lambda^0_{1,k}$, respectively. Because, the TMR is assumed to be positive for an upward offset, the upper track will provide a more reliable output than the lower track. Thus, if the signs of $\lambda^0_{-1,k}$ and $\lambda^0_{1,k}$ are different and the bits $\hat{x}_{-1,k}$ and $\hat{x}_{1,k}$ are the same, we will flip the sign of $\hat{x}_{1,k}$ to be opposite to that of $\hat{x}_{-1,k}$. With this additional step, the overall system performance can be improved because the lower track will yield fewer errors.



(a)

(b)

Fig. 5. Performance comparison of three data tracks without the jitter noise at AD $= 3.0$ Tb/in^2 for: (a) conventional three read heads; and (b) proposed systems.

IV. RESULT AND DISCUSSION

We compare the performance between the conventional three read head approach [5] and the proposed systems in the BPMR channel as shown in Fig. 2 at the AD of 3.0 Tb/in^2 (i.e., $T_x = T_z = 14.5$ nm), where the along-track PW$_{50}$ of 19.4 nm and the across-track PW$_{50}$ of 24.8 nm are considered. In simulation, the SNR is defined as SNR $= 20\log_{10}(1/\sigma)$ in dB.

Fig. 5 compares the performance of different systems by plotting the SNR required to achieve BER $= 10^{-4}$ as a function of TMR levels without position jitter. This paper assumes that the conventional system knows a TMR level and thus it can employ a correct pair of 2-D target and

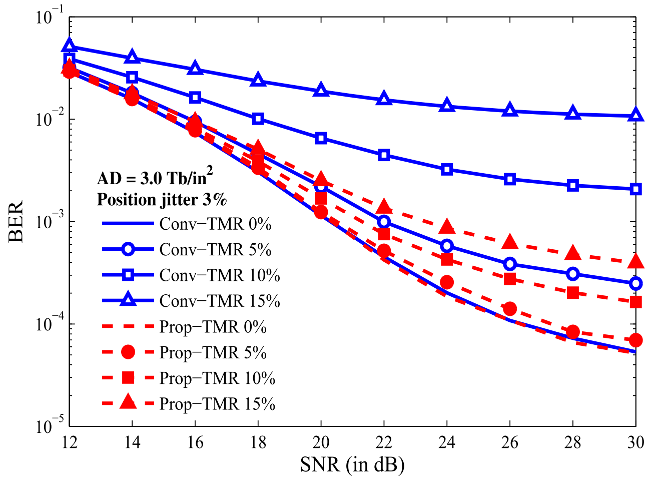


Fig. 6. BER performance comparison of different systems at AD = 3 Tb/in^2, where the position jitter is fixed at 3% for all TMR levels and BER curves are calculated as the average BER performance of all three tracks.

2-D equalizer in the data detection process. In addition, the three 2-D SOVA detectors are still used to detect data; however, the LLRs will not be utilized to improve the BER performance, similar to the work in [5]. For the conventional system, we can see in Fig. 5(a) that the center track yields the best performance but the upper and lower tracks still have poor performance. Clearly, the average performance of all three tracks is unacceptable because it requires the SNR higher than 28 dB to achieve the BER $= 10^{-4}$ for all TMR levels.

On the other hand, the overall system performance can be enhanced by using the proposed scheme, as shown in Fig. 5(b). It is apparent that the proposed system requires the SNR lower than 23 dB for the center and upper tracks to achieve the BER of 10^{-4}, while the lower track needs only 23.2 dB. Furthermore, the average performance of the proposed system is superior to that of the conventional system, especially when TMR is large (e.g., TMR $\geq$ 10%). Specifically, the proposed system requires only 21.5 dB while the conventional system needs the SNR more than 45 dB to achieve the BER $= 10^{-4}$.

We also investigate the BER performance of different systems in the presence of position jitter at AD $=$ 3 Tb/in^2 as shown in Fig. 6, which is present for both of the across and along track directions. Here, we denote the conventional system as "Conv-TMR N%" and the proposed system as "Prop-TMR N%," where N is the TMR level. Each BER curve is constructed from the average BER performance of all three data tracks, i.e., upper, center, and lower tracks. Evidently, the proposed system still performs better than the conventional system, in particular, when TMR is large.

V. CONCLUSION

To develop the TMR prediction and correction technique for ultra-high density BPMR, we utilize the readback signals from the upper and lower read heads, which are optimally moved closer to the center track, to estimate the TMR level. The TMR prediction is considered through the energy ratio computation, which can be used to predict the TMR level even in the presence of position jitter. Then, the TMR effect is alleviated by using the 2-D target and its corresponding 2-D equalizer that are the best suited for the estimated TMR level. Moreover, the soft-information exchange and bit-flipping techniques are also presented to improve the BER performance of all three data tracks simultaneously during the detection process. Numerical results show that the proposed system is superior to the conventional system.

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