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PAPER

A TMR Mitigation Method Based on Readback Signal in Bit-Patterned Media Recording

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SUMMARY Track mis-registration (TMR) is one of the major problems in high-density magnetic recording systems such as bit-patterned media recording (BPMR). In general, TMR results from the misalignment between the center of the read head and that of the main track, which can deteriorate the system performance. Although TMR can be handled by a servo system, this paper proposes a novel method to alleviate the TMR effect, based on the readback signal. Specifically, the readback signal is directly used to estimate a TMR level and is then further processed by the suitable target and equalizer designed for such a TMR level. Simulation results indicate that the proposed method can sufficiently estimate the TMR level and then helps improve the system performance if compared to the conventional receiver that does not employ a TMR mitigation method, especially when an areal density is high and/or a TMR level is large.

key words: *bit-patterned media recording, estimation method, signal-to-noise ratio, track mis-registration, two-dimensional equalization*

1. Introduction

Bit-patterned media recording (BPMR) is one of the promising recording technologies for the next generation's hard disk drives, which can achieve an areal density (AD) up to 4 Tera-bits per square inch (Tb/in^2) [1]. In BPMR, a data bit is stored in a single domain magnetic island, surrounded by non-magnetic material. To increase storage capacity, the spacing between the data bit islands in both the along- and the across-track directions must be decreased, thus leading to the increase of two-dimensional (2D) interference. In general, the 2D interference consisting of inter-symbol interference (ISI) and inter-track interference (ITI) [2] can considerably degrade the system performance if precautions are not taken.

In addition to the 2D interference, BPMR also encounters other challenging issues, including write synchronization error, media noise, and track mis-registration (TMR), which can further deteriorate the system performance. Therefore, a good read-channel design should provide robustness and reliability to tackle these issues. However, this paper focuses on how to mitigate the TMR effect, because it can significantly lead to performance degradation, especially in high-density BPMR systems.

Practically, TMR (or a head offset) is occurred when the center of the read head is not aligned with that of the main track [3], [4] as illustrated in Fig. 1. For example, the TMR could happen when the disk rotation speed is suddenly increased for high transfer rate and access time, while the read head moves to read data on the main track [5]. Generally, the TMR can yield a devastating impact on the data recovery process because it causes an unequal effect of the adjacent tracks on the main track, thus lowering the quality of the readback signal. Moreover, the TMR effect results in the mismatch between the readback signal and the design of the target and its corresponding equalizer, which in turn causes the detector to perform unreliably.

In general, the TMR can be controlled by a servo system [4], [5]. Specifically, a servo burst field has the information that can be used to estimate the amount of head offset, but it is difficult to estimate the behavior of the read head when the TMR occurred beyond the limit [5]. Alternatively, Myint and Supnithi [6] detected the presence of TMR from the readback signal based on the observation of 2D target-shaping equalizer coefficients, and then adjusted the 2D target and equalizer to be asymmetric so as to taken care of the TMR-affected readback signal. Nevertheless, we found that the method in [6] cannot accurately estimate the TMR level, and both the 2D target and equalizer are not efficiently matched with the BPMR channel with TMR, thus leading to the performance degradation at the data detection process.

To solve this problem, this paper proposes a novel

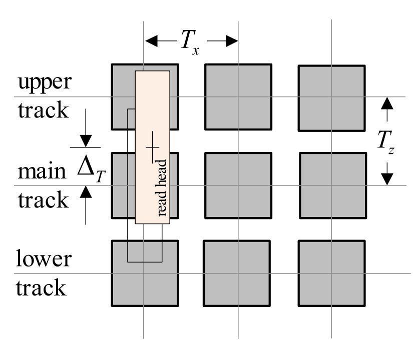

Fig. 1 The illustration of island structure configuration in a BPMR system with track mis-registration (TMR), Δ_T.

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method to mitigate the TMR effect based on the readback signal. To do so, we study the statistical relationship among the readback signal, a signal-to-noise ratio (SNR), and TMR amount for various cases. Next, we formulate the mathematical equations so as to estimate the SNR and the TMR level based on the readback signal. Specifically, the SNR is estimated from the average peak readback amplitude, whereas the TMR level is computed from the estimated SNR and the energy of the readback signal. Then, the estimated TMR level will be utilized to choose the target and its corresponding equalizer from a look-up table that are suitable for the channel with TMR so as to facilitate the data detection process. Note that each pair of the target and its equalizer is designed for each TMR level and is stored in the look-up table.

The rest of this paper is organized as follows. Section 2 briefly describes a BPMR channel model, and Sect. 3 explains the proposed method. Simulation results are given in Sect. 4. Finally, Sect. 5 concludes this paper.

2. BPMR Channel Model

This work focuses on a discrete-time BPMR channel model with multi-track processing [7], as depicted in Fig. 2. A binary input data sequence $x_{l,k} \in \{\pm 1\}$ with bit period T_x, where $l = 0$ is the main track, $l = -1$ is the upper track, and $l = 1$ is the lower track, is sent to the BPMR channel corrupted by TMR and electronics noise modeled as an additive white Gaussian noise (AWGN). Then, the readback signal of the kth data bit on the lth track can be expressed as

$$\begin{aligned} r_{l,k} &= x_{l,k} \otimes h_{l,k} + w_{l,k} \\ &= \sum_m \sum_n h_{m,n} x_{l-m,k-n} + w_{l,k}, \end{aligned} \tag{1}$$

where $x_{l,k}$'s are the recorded bits, $h_{m,n}$'s are the 2D channel coefficients, m and n represent the time indices of the bit island in the across- and the along-track directions, and $w_{l,k}$ is an AWGN with zero mean and variance σ^2.

Practically, the BPMR channel coefficients $h_{m,n}$ can be generated by sampling a 2D Gaussian pulse response at the integer multiples of the bit period T_x and the track pitch T_z according to

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

where $P(z, x)$ is the 2D Gaussian pulse response, z and x are the time indices in the across- and the along-track directions, $\{m, n\} \in (-L, \ldots, 0, \ldots, L)$, $2L + 1$ is the length of $P(z, x)$, L is an integer, and Δ_T is the head offset or the distance between the center of the read head and that of the main track as depicted in Fig. 1. Generally, L should be large enough to ensure that the tail amplitude of $P(z, x)$ is small, where this paper considers $L = 1$ for simplicity.

In this paper, the TMR level is defined as

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

where the sign of Δ_T is assumed to be positive for the upward offset as shown in Fig. 1. Furthermore, we consider the 2D Gaussian pulse response of the form [2]

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

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, and $c = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian pulse.

In a conventional receiver that does not employ a TMR mitigation method, the readback signal $r_{l,k}$ for $l \in \{0, \pm 1\}$ is fed to a 2D equalizer followed by a 2D Viterbi detector to determine the most likely input sequence on the main track, i.e., $\hat{x}_{0,k}$. Note that this paper does not take media noise into account and considers only the system that recovers the recorded data on the main track, as similar to [6]. Hence, three adjacent readback signals $\{r_{-1,k}, r_{0,k}, r_{1,k}\}$ at the input of a 2D equalizer, $\mathbf{F}$, are required to generate a single output $\{z_{0,k}\}$, whereas three input data sequences $\{x_{-1,k}, x_{0,k}, x_{1,k}\}$ are sent to a 2D target, $\mathbf{G}$, to output the desired data sequence $\{d_{0,k}\}$.

3. Proposed Method

We propose a novel method to subside the TMR effect in a BPMR channel, based on the readback signal. Specifically, we first estimate a TMR level with an aid of the estimated SNR and the average energy of the readback signal. Hence, the target and its corresponding equalizer suitable for the channel with TMR are selected according to the estimated TMR level so as to ease the data recovery process. The details of the proposed method can be explained as follows.

3.1 SNR Estimation

In this paper, the SNR is defined as [8]

$$\text{SNR} = 20\log_{10}(V_p/\sigma), \tag{5}$$

in decibel (dB), where V_p is the peak amplitude of the readback signal, which is assumed to be 1, and σ is a standard deviation of AWGN. This SNR will be estimated before predicting the amount of the TMR. Here, we propose to estimate the SNR from the peak amplitude of the readback signal. To do so, we collect a large number of samples (e.g., 1000 samples) of the readback signals at each SNR ranged from 0 to 25 dB, where each readback signal is affected by a uniformly distributed random TMR level ranged from 0% to 25%. Then, for each SNR, the average value of the peak amplitude of all readback signals, r_{peak}, is computed, regardless of TMR levels.

Figure 3 illustrates the relationship between the SNR and the average peak amplitude of the readback signals at the AD of 2.0 Tb/in^2, where we found that the SNR can be

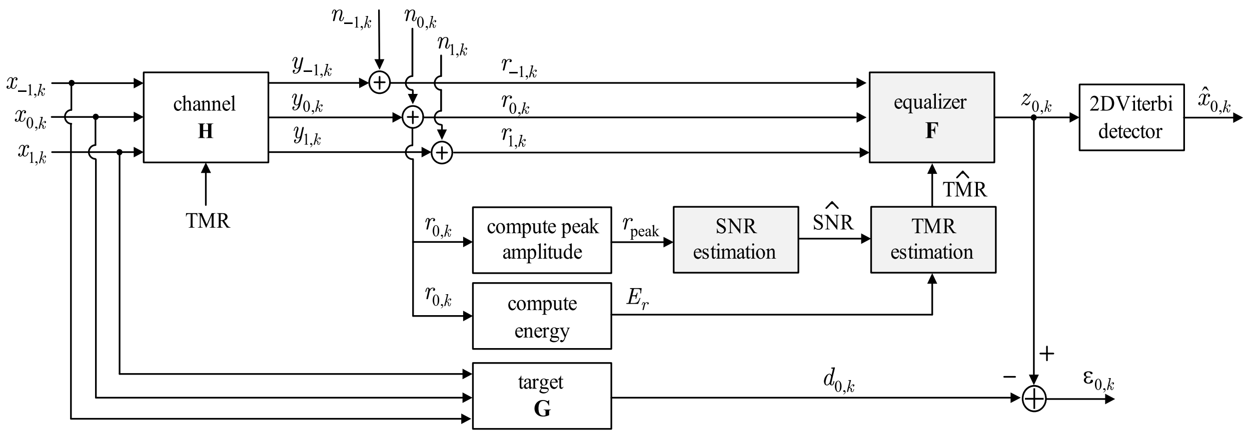

Fig. 2 A BPMR channel model with the proposed TMR mitigation method.

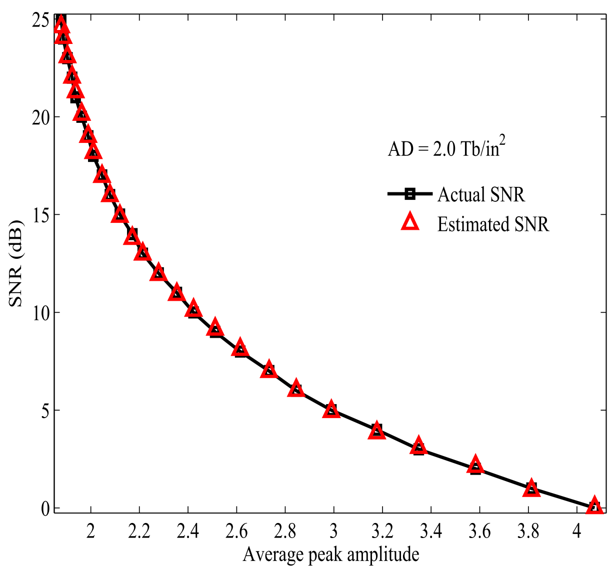

Fig. 3 The relationship between the SNR and the average peak amplitude of the readback signals at AD = 2.0 Tb/in^2.

possibly approximated. To achieve this, we apply a least-squares (LS) fitting technique to fit all data points to an M-degree polynomial equation according to

$$\hat{\text{SNR}} = a_0 + a_1 r_{\text{peak}} + a_2 r_{\text{peak}}^2 + \ldots + a_M r_{\text{peak}}^M, \quad (6)$$

where $\hat{\text{SNR}}$ is the estimated SNR, a_i is the ith coefficient of the polynomial equation in (6), and $i \in \{0, 1, \ldots, M\}$. Based on extensive heuristic search, we found that $M = 5$ is sufficient for our channel model at the AD up to 3.0 Tb/in^2 because a higher order does not provide any benefit on the accuracy of SNR estimation. As depicted in Fig. 3, it is apparent that the estimated SNR effectively coincides with the actual SNR.

3.2 TMR Estimation

For each SNR, we also propose to employ the energy of the readback signal to estimate the TMR level. To do so, we compute the average energy of the readback signal, E_r, for each SNR and TMR level according to

$$E_r = \frac{1}{S} \sum_{k=1}^{S} r_{0,k}^2, \quad (7)$$

where S is the length of the readback signal samples (i.e., $S = 32768$ bits for a 4K-data sector [9]). Next, the estimated TMR level is obtained based on a polynomial LS fitting technique, i.e.,

$$\hat{\text{TMR}} = b_0 + b_1 E_r + b_2 E_r^2 + \ldots + b_Q E_r^Q, \quad (8)$$

where $\hat{\text{TMR}}$ is the estimated TMR, b_i and Q are the ith coefficient and a degree of the polynomial equation in (8), respectively, and $i \in \{0, 1, \ldots, Q\}$. Similarly, we perform an extensive simulation search to find a suitable Q, where $Q = 5$ provides the best fit between the actual and the estimated TMR levels.

Figure 4 shows the estimated TMR level as a function of the average energy of the readback signal at the AD of 2.0 Tb/in^2 for various SNRs. Clearly, the TMR level can be effectively estimated from (8) based on $\hat{\text{SNR}}$ and E_r.

3.3 Equalizer and Target Design

The target and its corresponding equalizer used in this work are designed for each TMR level based on minimizing a mean-squared error (MSE) [10] according to

$$E\left\{\varepsilon_{l,k}^2\right\} = E\left\{(z_{l,k} - d_{l,k})^2\right\}, \quad (9)$$

where $E\{.\}$ is an expectation operator, and $\varepsilon_{l,k}$ is an error signal between the equalizer output $z_{l,k}$ and the desired output $d_{l,k}$. By expanding the right-hand side in (9), we obtain

$$\begin{aligned} E\left\{\varepsilon_{l,k}^2\right\} &= E\left\{[(r_{l,k} \otimes f_{l,k}) - (x_{l,k} \otimes g_{l,k})]^2\right\} \\ &= f_{l,k} \otimes R_{l,k}^r \otimes f_{l,k} - 2 f_{l,k} \otimes R_{l,k}^{rx} \otimes g_{l,k} \\ &\quad + g_{l,k} \otimes R_{l,k}^x \otimes g_{l,k}, \end{aligned} \quad (10)$$

where $\otimes$ is the 2D convolution operator, $R_{l,k}^r = E\left\{r_{i,j} r_{i-l,j-k}\right\}$ and $R_{l,k}^x = E\{x_{i,j} x_{i-l,j-k}\}$ are the auto-correlations of the readback signals and the recorded bits from all three tracks, respectively, and $R_{l,k}^{rx} = E\{r_{i,j} x_{i-l,j-k}\}$ is the cross-correlation

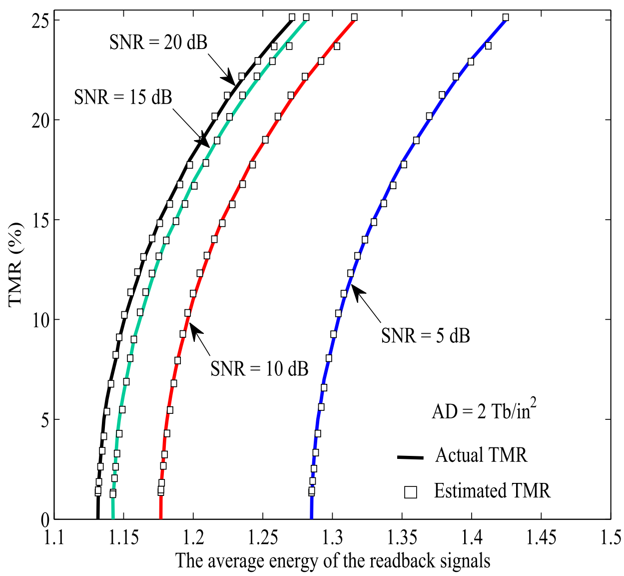

Fig. 4 The relationship between the TMR level and the average energy of the readback signals at AD = 2.0 Tb/in^2.

between the readback signals and the recorded bits.

To find the solution of (10), it is convenient to represent the matrices in the vector forms [10]. To do so, we let $\mathbf{F}$ be a $3 \times (2N+1)$ equalizer matrix of the form

$$\mathbf{F} = \begin{bmatrix} \mathbf{f}_{-1} \\ \mathbf{f}_0 \\ \mathbf{f}_1 \end{bmatrix} = \begin{bmatrix} f_{-1,-N} & f_{-1,0} & f_{-1,N} \\ f_{0,-N} & f_{0,0} & f_{0,N} \\ f_{1,-N} & f_{1,0} & f_{1,N} \end{bmatrix}, \quad (11)$$

where $f_{l,k}$'s are the equalizer coefficients, $l \in \{0, \pm1\}$ is the track location, $k \in \{-N, \ldots, 0, \ldots, N\}$, and $2N+1$ is the equalizer length. Similarly, let $\mathbf{G}$ be a 3×3 target matrix of the form

$$\mathbf{G} = \begin{bmatrix} \mathbf{g}_{-1} \\ \mathbf{g}_0 \\ \mathbf{g}_1 \end{bmatrix} = \begin{bmatrix} g_{-1,-1} & g_{-1,0} & g_{-1,1} \\ g_{0,-1} & g_{0,0} & g_{0,1} \\ g_{1,-1} & g_{1,0} & g_{1,1} \end{bmatrix}, \quad (12)$$

where $g_{l,k}$'s are the target coefficients, $l \in \{0, \pm1\}$ is the track location, and $k \in \{-1, 0, 1\}$.

In general, the matrices $\mathbf{F}$ and $\mathbf{G}$ can be rearranged into the column vectors as $\mathbf{f} = [\mathbf{f}_{-1}\ \mathbf{f}_0\ \mathbf{f}_1]^{\mathrm{T}}$ and $\mathbf{g} = [\mathbf{g}_{-1}\ \mathbf{g}_0\ \mathbf{g}_1]^{\mathrm{T}}$, respectively, where the component vectors are defined in (11) and (12), and $[\cdot]^{\mathrm{T}}$ is a transpose operator. Using these matrices, the MSE in (10) can be rewritten as

$$E\left\{\varepsilon_{l,k}^2\right\} = \mathbf{f}^{\mathrm{T}}\mathbf{R}_r\mathbf{f} - 2\mathbf{f}^{\mathrm{T}}\mathbf{R}_{rx}\mathbf{g} + \mathbf{g}^{\mathrm{T}}\mathbf{R}_x\mathbf{g}, \quad (13)$$

where $\mathbf{R}_r = [\mathbf{r}_k\mathbf{r}_k^{\mathrm{T}}]$ is a $3(2N+1)\times3(2N+1)$ auto-correlation matrix of $R_{l,k}^r$, $\mathbf{r}_k$ is the readback signal vector, $\mathbf{R}_{rx} = [\mathbf{r}_k\mathbf{x}_k^{\mathrm{T}}]$ is a $3(2N+1) \times 9$ cross-correlation matrix of $R_{l,k}^{rx}$, $\mathbf{x}_k$ is the recorded bit vector, and $\mathbf{R}_x = [\mathbf{x}_k\mathbf{x}_k^{\mathrm{T}}]$ is a 9×9 auto-correlation matrix of $R_{l,k}^x$.

Because we focus only on detecting the data on the main track (i.e., $l = 0$), the MSE in (9) can then be computed by

$$E\{\varepsilon_{0,k}^2\} = E\{(z_{0,k} - d_{0,k})^2\}. \quad (14)$$

Hence, in this case, the readback signal vector and the recorded bit vector will be given by $\mathbf{r}_k = [r_{1,k+N}\ r_{1,k+N-1}\ \ldots\ r_{0,0}\ \ldots\ r_{-1,k-N+1}\ r_{-1,k-N}]^{\mathrm{T}}$ and $\mathbf{x}_k = [x_{1,k+1}\ x_{1,k}\ \ldots\ x_{0,0}\ \ldots\ x_{-1,k}\ x_{-1,k-1}]^{\mathrm{T}}$, respectively.

During the minimization process of the MSE in (13), we impose a constraint of $\mathbf{e}^{\mathrm{T}}\mathbf{g} = 1$ to avoid reaching trivial solutions of $\mathbf{f} = \mathbf{g} = \mathbf{0}$, where $\mathbf{e} = [0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0]^{\mathrm{T}}$ is a column vector with 9 entries. Accordingly, $\mathbf{f}$ and $\mathbf{g}$ are chosen such that

$$\begin{aligned} E\left\{\varepsilon_{0,k}^2\right\} = {} & \mathbf{f}^{\mathrm{T}}\mathbf{R}_r\mathbf{f} - 2\mathbf{f}^{\mathrm{T}}\mathbf{R}_{rx}\mathbf{g} + \mathbf{g}^{\mathrm{T}}\mathbf{R}_x\mathbf{g} \\ & -2\lambda^{\mathrm{T}}(\mathbf{e}^{\mathrm{T}}\mathbf{g} - 1) \end{aligned} \quad (15)$$

is minimized, where λ is a Lagrange multiplier [10], [11]. Then, the minimization process gives

$$\lambda = \frac{1}{\mathbf{e}^{\mathrm{T}}(\mathbf{R}_x - \mathbf{R}_{rx}^{\mathrm{T}}\mathbf{R}_r^{-1}\mathbf{R}_{rx})^{-1}\mathbf{e}} \quad (16)$$

$$\mathbf{g} = \lambda(\mathbf{R}_x - \mathbf{R}_{rx}{}^{\mathrm{T}}\mathbf{R}_r^{-1}\mathbf{R}_{rx})^{-1}\mathbf{e} \quad (17)$$

$$\mathbf{f} = \mathbf{R}_r^{-1}\mathbf{R}_{rx}\mathbf{g}. \quad (18)$$

Note that if the target $\mathbf{g}$ is given, one can still employ (18) to obtain the equalizer $\mathbf{f}$ that minimizes the MSE in (15).

3.4 TMR Mitigation Methods

In this work, we propose two methods to mitigate the TMR effect based on the structure of the 2D target (i.e., symmetric or asymmetric). Then, the performance of the proposed methods will be compared with that of a conventional receiver, which employs fixed 2D target and equalizer designed for 0% TMR level. Without TMR and media noise, the channel response in (2) will normally be symmetric, and we found that the 2D target $\mathbf{G}$ obtained from this design is also *symmetric* because the target coefficients $\mathbf{g}_{-1}$ and $\mathbf{g}_1$ in (12) are almost equal.

For the first proposed method (denoted as the *symmetric* system), the symmetric 2D target as used in the conventional receiver is employed, but the equalizer is selected according to the estimated TMR level. To do so, we need to design the equalizers suitable for each TMR level based on (18), where the target is fixed, and store them in the look-up table. On the other hand, the second proposed method (denoted as the *asymmetric* system) utilizes the 2D target and its corresponding equalizer specially designed for each TMR level according to (16) – (18), where we refer to this 2D target as the *asymmetric* target because the target coefficients $\mathbf{g}_{-1}$ and $\mathbf{g}_1$ in (12) are not equal. Thus, each pair of the target and equalizer associated with a given TMR level will be kept in the look-up table. Table 1 shows an example of the coefficients of the asymmetric 2D targets for some TMR levels at the ADs of 2.0 and 3.0 Tb/in^2, which are used in this paper.

It should be pointed out that the 2D Viterbi detector is designed for the asymmetric 2D target [11] as illustrated in Table 1. The three bits from the three adjacent tracks (upper, main, and lower tracks) are sensed by the read head so that

Table 1 The coefficients of the asymmetric 2D targets for some TMR levels at the ADs of 2.0 and 3.0 Tb/in^2.

TMR (%)	2D target coefficients, **G** 2.0 Tb/in^2			3.0 Tb/in^2		
0%	0.0201	0.2187	0.0201	0.0692	0.3255	0.0692
	0.0866	0.9422	0.0866	0.1785	0.8398	0.1785
	0.0201	0.2187	0.0201	0.0692	0.3255	0.0692
5%	0.0232	0.2526	0.0232	0.0759	0.3571	0.0759
	0.0864	0.9402	0.0864	0.1781	0.8381	0.1781
	0.0173	0.1886	0.0173	0.0628	0.2955	0.0628
10%	0.0267	0.2904	0.0267	0.0829	0.3902	0.0829
	0.0859	0.9343	0.0859	0.1770	0.8238	0.1770
	0.0149	0.1619	0.0149	0.0567	0.2671	0.0567
20%	0.0348	0.3784	0.0348	0.0977	0.4598	0.0977
	0.0836	0.9090	0.0836	0.1725	0.8120	0.1725
	0.0108	0.1176	0.0108	0.0458	0.2154	0.0458

each symbol represents these three bits resulting 8 combinations in total. The asymmetric 2D target has the current and 2 previous symbols (i.e., 2 memory taps) giving 8^2 = 64 states. Therefore, its trellis has 64 states and 8 outgoing branches from each state.

4. Simulation Results

We study the performance of the proposed methods (both the symmetric and the asymmetric systems) in the BPMR system shown in Fig. 2 at the ADs of 2.0 and 3.0 Tb/in^2, where both the bit period and the track pitch are $T_x = T_z = 18$ and 14.5 nm, respectively. Additionally, this paper considers 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, similar to [8]. Each bit-error rate (BER) point is computed using as many 4K-data sectors as required to collect a minimum number of 500 error bits. Furthermore, the accuracy of TMR estimation is measured by

$$\text{Accuracy}(\%) = 100 - \frac{\left|\hat{\text{TMR}} - \text{TMR}\right|}{\text{TMR}} \times 100, \qquad (19)$$

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

Figure 5 demonstrates the TMR estimation accuracy (in percentage) of the proposed method in BPMR system at the AD of 2.0 Tb/in^2. Clearly, the proposed method can provide a good estimation of TMR level, especially when TMR is large and SNR is high. For example, it is possible to achieve 95% accuracy of TMR estimation when SNR is greater than 15 dB and TMR is larger than 15%. Therefore, it can be implied that the proposed method can be effectively used to estimate the actual TMR embedded in the readback signal, especially when SNR and TMR are high. Moreover, we found that the estimation accuracy is less than 40% when TMR and SNR are small. This might be because the effect of TMR ranged from 0% to 5% is very similar and AWGN is dominated because of low SNR.

We also compare the BER performance of the proposed systems with the conventional system for various ADs and

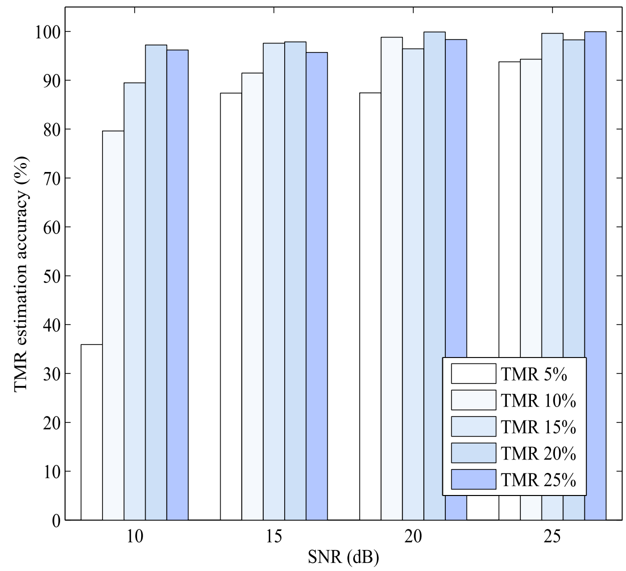

Fig. 5 The relationship between the SNR levels and the percentage of the estimation accuracy of the proposed method at AD = 2.0 Tb/in^2.

various TMR effect levels. The curve labeled "Conv-TMR 0%" represents the conventional system without TMR effect, which yields the best performance, and the curves labeled "Conv-TMR 5%", "Conv-TMR 10%", and "Conv-TMR 20%" represent the conventional system with TMR effect at 5%, 10%, and 20%, respectively. Moreover, the curve labeled "Proposed-Sym-TMR *X*%" represents the proposed method with a symmetric target at the TMR level of *X*%, whereas the curve labeled "Proposed-Asym-TMR *X*%" denotes the proposed method with an asymmetric target at the TMR level of *X*%.

At AD = 2.0 Tb/in^2, the results show that the proposed methods (symmetric and asymmetric systems) yield slightly better performance than the conventional system for all TMR levels, as illustrated in Fig. 6 and Fig. 7. However, we can obtain a higher performance gap when the AD is increased, e.g., at AD = 3.0 Tb/in^2. Specifically, when AD increases, not only the ITI effect is more severe, but also the TMR can easily occur in the system even though the read head slightly moves away from the main track. Fortunately, the proposed method can handle the severe TMR effect. We can see that the symmetric system performs slightly better than the conventional system at 5% TMR level and offers the performance gain about 4 dB at BER = 10^{-4} and 10% of the TMR level; however, both the conventional and the symmetric systems cannot provide satisfactory performance for high TMR levels, as demonstrated in Fig. 8. On the other hand, the asymmetric system is superior to the conventional system, especially when TMR is high. Specifically, it can provide a performance gain over the conventional system about 0.5 and 6 dB at BER = 10^{-4} for the TMR level of 5% and 10%, respectively, as shown in Fig. 9. Therefore, it is of importance to notice that the proposed TMR estimation method can be also well performed when it encounters with some media noise, e.g., position jitter (not shown here).

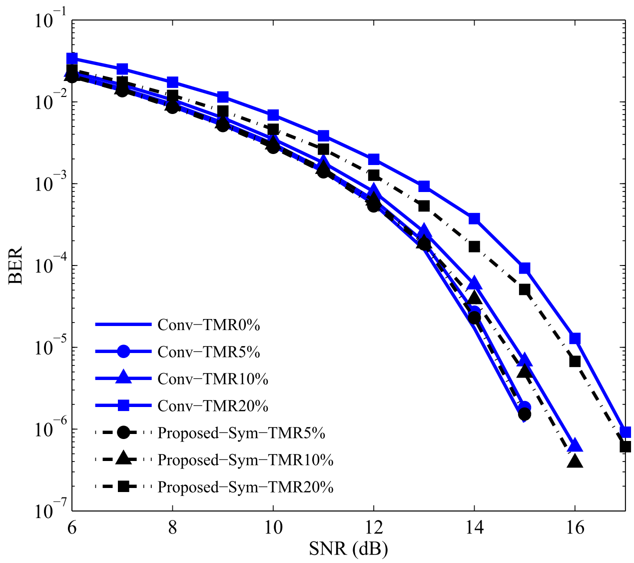

Fig. 6 BER performance between the conventional and the symmetric systems at AD = 2.0 Tb/in^2 for various TMR levels.

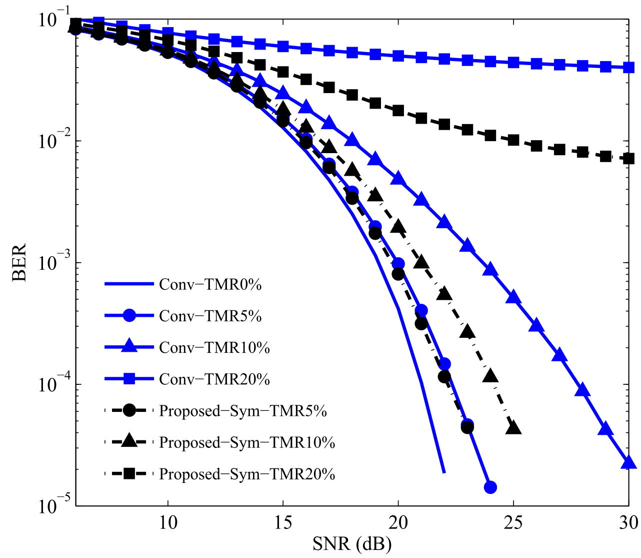

Fig. 8 BER performance between the conventional and the symmetric systems at AD = 3.0 Tb/in^2 for various TMR levels.

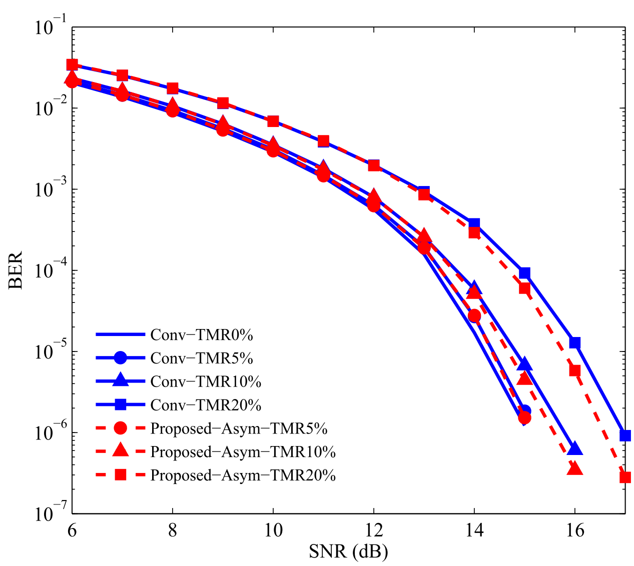

Fig. 7 BER performance between the conventional and the asymmetric systems at AD = 2.0 Tb/in^2 for various TMR levels.

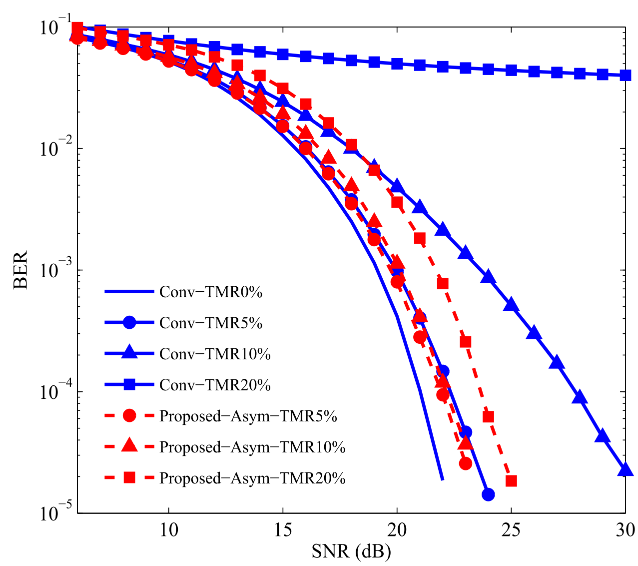

Fig. 9 BER performance between the conventional and the asymmetric systems at AD = 3.0 Tb/in^2 for various TMR levels.

Consequently, it can be implied that the proposed methods perform better than the conventional receiver because the detection process utilizes the 2D target and its corresponding equalizer that match with the BPMR channel with TMR. Nevertheless, the proposed methods require some extra memory to store the 2D target and the equalizer that are suitable for each TMR level.

5. Conclusion

This paper proposes the TMR mitigation method for a high-density BPMR system. It starts with estimating the SNR based on the average peak amplitude of the readback signals. Then, the estimated TMR level can be calculated based on the estimated SNR and the average energy of the readback signals. Once the TMR level is known, we can choose the target and its corresponding equalizer that match with the BPMR channel with TMR in the data detection process so as to obtain a good system performance. Simulation results indicate that the proposed system can effectively estimate the TMR level, and it performs better than the conventional system, especially when the SNR and TMR are large.

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