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Single-Track equalization method with TMR correction system based on cross correlation functions for a patterned media recording system

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Abstract

Bit-patterned media recording (BPMR) is a promising technology for ultra-high density media, however, there are some challenges that need to be addressed including two-dimensional (2D) interference, and track mis-registration (TMR). The system can experience TMR due to misalignment of the head and the track center. Conventionally, TMR is tackled using a servo system in which the head position offset is estimated by processing the overhead servo sequences before reading the data sequences. However, TMR impairment can also occur when the head is reading data sequences that are beyond the servo mechanism. To address this problem, we proposed TMR detection and correction techniques based on our previous work involving a single-track equalization method for a BPMR system using cross-correlation functions between the single readback signal and each of the training sequences from three adjacent tracks. In this proposed technique, the presence and level of TMR is detected and estimated based on the changes in the value of mean square error (MSE) between the equalized and feedback signals from the detectors after passing through a one-dimensional (1D) target for each sequence. Then, the estimated TMR levels are used in selecting the appropriate equalizer and the generalized partial response (GPR) target pair to tackle the TMR from the readback signal. The simulation results show improvement in the data recovery of a BPMR system using the proposed method when the system is experiencing 2D interference and TMR impairment.

Keywords: Bit-patterned media recording, Track mis-registration, Equalization, Inter-track interference, Inter-system interference

1. Introduction

Bit-patterned media recording (BPMR) is one of promising technologies for the next generation ultra-high density beyond the superparamagnetic limit [1]; however, it has some challenges to be addressed before realizing the appreciation of its high areal density property. One of them is a two-dimensional (2D) interference which consists of inter-symbol interference (ISI) and inter-track interference (ITI). The 2D interference is getting more severe while its areal density is increased. Another major challenge in BPMR is the off-track condition or track mis-registration (TMR) due to the misalignment of the read head from the track center [2].

Conventionally, a servo mechanism is applied to evaluate and control TMR to the acceptable level [3] by processing the overhead servo information sequences recorded on the media ahead of the data sequences. However, the system can easily experience with TMR not only at the beginning of read process but also at any time during reading the data sequences on the track because the disk rotation speed is suddenly increased for high transfer rate or other reason when moving along the data track. In practice, it is difficult to detect the presence of TMR or approximate the behavior of the read head when TMR occurred beyond the servo limitation, which results in a devastating effect on the data recovery system.

In literatures, utilizing a multi-track 2D equalization and a multi-track or 2D detection [3-4] in the data recovery system has been proposed to tackle this problem but they achieve the performance gain by processing with multi-readback signals from a conceived multi-head or array-head. Since the multi-head is still infeasible with the current technology, researchers have also proposed a joint-track equalization method in which a 1D equalizer is applied together in conjunction with a 2D generalized partial response (GPR) target for the current single head system. In this system, minimum mean squared error (MMSE) technique does not improve the performance of the detector compared to 1D GPR target system. Therefore, we proposed a novel equalizer design with ISI/ITI estimation schemes based on cross-correlation functions [5]. Assuming that three known (or training) bit sequences recorded on three adjacent tracks and only single readback signal from the target track can be available during the designing process of the target and equalizer, the estimated channel's coefficients are

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computed first based on three correlation functions between the read back signal and each of three known bit sequences during the target and equalizer design process. Unlike the conventional target design described in [4] where both of the 2D GPR target and the equalizer are designed simultaneously, we build the 2D GPR target in [5] with the estimated channel's coefficients and thereafter design the equalizer to match the 2D GPR target based on an MMSE criterion. According to the simulation results, the proposed equalization method in [5] yields the performance gain over the conventional joint-track equalization from [3-4]. However, the TMR effect is not considered.

In this paper, we study the performance of the previous proposed single-track equalization and detection from [5] for BPMR channel model with TMR effect. Since the performance of the data recovery system can be degraded when the mismatch between the channel and the target is encountered due to the head's misalignment occurred during reading the data sequence that is beyond servo control mechanism. To tackle this problem, we propose a TMR detection and estimation technique based on checking the value of mean square error (MSE) between the equalized signal and the estimated desired signal from the target, generated by processing the feedback signal from the detector through 1-D target. Moreover, the proposed technique can correct the target and the equalizer according to the estimated TMR level.

2. BPMR channel model with equalization method

In this work, a discrete channel model of BPMR system is considered, as shown in Figure 1. Similar to [5], the readback signal, $r_{k,0}$of the k^{th} data bit on the main track can be expressed as

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

where $h_{m,n}$'s are the 2D channel coefficients and $w_{k,0}$ is an additive white Gaussian noise (AWGN) sequence with zero mean and variance σ^2. The 2D channel response coefficients $h_{m,n}$ of the BPMR system are generated by sampling the 2D Gaussian pulse response at integral multiples of bit period T_x and track pitch T_z, i.e.,

$$h_{m,n} = A\exp\left\{-0.5\left[\left(nT_x / c\text{PW}_x\right)^2 + \left(m\left(T_z + \Delta\tau\right)/ c\text{PW}_z\right)^2\right]\right\}, \tag{2}$$

where A = 1 is the maximum amplitude of 2D Gaussian pulse response, PW_x is the PW_{50} of the along-track pulse response direction, PW_z is the PW_{50} of the cross-track pulse response direction, c = 1/2.3548 is a constant, and $\Delta\tau$ is a head offset. The head offset is assumed to be positive for the upward offset. In this paper, the percentage of TMR level is defined with the value of head offset $\Delta\tau$ as $\text{TMR}(\%) = (\Delta\tau \,/\, T_z) \times 100$.

In the system model, the random binary (i.e.,−1 and +1) bit sequences, $x_{k,0}$, $x_{k,-1}$, and $x_{k,1}$are recorded on the main track and the two adjacent tracks, respectively. In the data recovery side, the readback signal $r_{k,0}$is equalized with the proposed equalizer from [5] to obtain an equalized data sequence, $z_{k,0}$ and then, it is sent to a Viterbi detector, which employs a trellis constructed based on the obtained 2D GPR target, to generate the estimated recorded bits $\hat{x}_{k,0}$.

Taking into account the ISI from two adjacent islands along the main track and the ITI from two adjacent tracks, BPMR channels can be represented by a 3×3 symmetric channel matrix as shown below.

$$\mathbf{H} = \left[\begin{bmatrix} h_{-1,-1} & h_{-1,0} & h_{-1,1} \end{bmatrix}^{\mathrm{T}} \; \begin{bmatrix} h_{0,-1} & h_{0,0} & h_{0,1} \end{bmatrix}^{\mathrm{T}} \; \begin{bmatrix} h_{1,-1} & h_{1,0} & h_{1,1} \end{bmatrix}^{\mathrm{T}}\right], \tag{3}$$

where $h_{l,-1}$and $h_{l,1}$with $l \in \{0,\pm1\}$ are the ITI coefficients due to adjacent tracks and $h_{-1,0}$ and $h_{1,0}$ are the ISI coefficients, and $[\cdot]^{\mathrm{T}}$ represents the matrix transpose operation. During the equalizer designing process, the three recorded bit sequences on the main (or target) track, the upper track, and the lower track are known by the system. To estimate the coefficients in the 2$^{\text{nd}}$ row of matrix in (3), we compute the cross-correlation function between the readback signal $r_{k,0}$from the target track and the known recorded bits sequence $x_{k,0}$ for the main track, $R_j^{r_0 x_0}$, i.e.,

$$\begin{aligned} R_j^{r_0 x_0} &= E\left\{r_{k,0} x_{k-j,0}\right\} = h_{k,-1} * E\left\{x_{k,-1} x_{k-j,0}\right\} \\ &+ h_{k,0} * E\left\{x_{k,0} x_{k-j,0}\right\} + h_{k,1} * E\left\{x_{k,1} x_{k-j,0}\right\} + E\left\{w_{k,0} x_{k-j,0}\right\}, \end{aligned} \tag{4}$$

where $E\{\cdot\}$ is the expectation operator and $*$ is the convolution operator. Given that the recorded bit sequences on different tracks are uncorrelated to each other and the noise $w_{k,0}$ isan AWGN, the cross-correlations, $E\{x_{k,-1}x_{k-j,-0}\}$, $E\{x_{k,1}x_{k-j,0}\}$, and $E\{w_{k,0}x_{k-j,0}\}$ in (4) can be ignored and the auto-correlation, $E\{x_{k,0}x_{k-j,0}\}$can also be assumed to be 1. By considering these assumptions, the channel coefficients can be approximated by $R_j^{r_0 x_0}$ which is the cross-correlation function in (4) for $j \in \{0,\pm1\}$. Similarly, the upper and the lower ITI coefficients of the channel matrix in (3) can also be estimated by the cross-correlation functions, $R_j^{r_0 x_{-1}}$ and $R_j^{r_0 x_1}$ which are computed between the readback signal, $r_{k,0}$from the main track and the recorded bits sequence, $x_{k,-1}$ of the upper track, and the known recorded bits sequence,

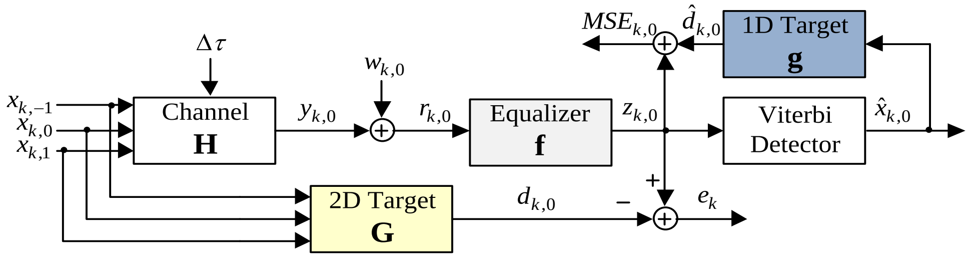

Figure 1 Block diagram of BPMR system with the proposed scheme.

$x_{k,1}$ of the lower track, respectively. Assuming that the channel is invariant, the fixed 2D GPR target matrix G with the size of 3×3 is constructed with the respective correlation functions, i.e.,

$$\mathbf{G} = \left[\left[R_{-1}^{r_0 x_{-1}} \; R_{-1}^{r_0 x_0} \; R_{-1}^{r_0 x_1} \right]^{\mathrm{T}} \left[R_{0}^{r_0 x_{-1}} \quad R_{0}^{r_0 x_{-1}} \quad R_{0}^{r_0 x_1} \right]^{\mathrm{T}} \left[R_{1}^{r_0 x_{-1}} \; R_{1}^{r_0 x_0} \; R_{1}^{r_0 x_1} \right]^{\mathrm{T}} \right]. \tag{5}$$

Finally, an equalizer matrix **f** with the size (2*N*+1)×1 as **f** = [f_{-N}... f_0... f_N], for this target is constructed according to the MMSE criterion as described in [3-4].

3. TMR estimation and correction technique

To detect and estimate TMR (head offset) during reading a data sequence, the estimated sequence, $\hat{x}_{k,0}$ from the Viterbi detector is fed back to the target. In here, only one single sequence is available from the detector; hence, the center row of the target matrix (1D target **g** in Figure 1), is used to estimate the desired signal sequence from the target. Then the mean squared error, $MSE_{k,0}$, between the estimated desired sequence, $\hat{d}_{k,0}$ generated by processing the estimated sequence from the detector with a 1D target **g** and the equalized sequence, $z_{k,0}$ is computed. Although the 1D target **g** is used in this TMR estimation, the difference between the values of the current data sequence's MSE ($MSE_{k,0}$) and that of previous sequence ($MSE_{k-1,0}$) is negligibly small. However, when the read channel is affected by TMR impact during its moving between the data sequences, the mismatch between the channel and the target due to TMR will result the significant difference between $MSE_{k,0}$ and $MSE_{k-1,0}$. Therefore, the proposed technique detects the present of TMR observing the changes of difference between the *MSE*s from two consecutive sequences. For TMR estimating mechanism, the proposed method computes the values of *MSE* difference between the estimated sequence of the system without TMR and with each of the TMR levels. Those computed values are recorded to use as the threshold values. If TMR is detected at a new sequence, the value of difference between two *MSE*s is compared with each of the stored threshold values to estimate

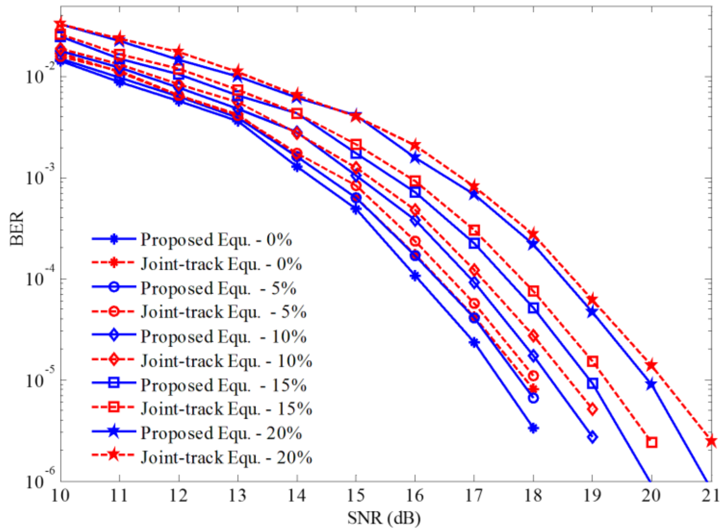

Figure 2 The performance comparison of our proposed equalization in [5] and joint-track equalization in [4] for a BPMR system with various TMR levels.

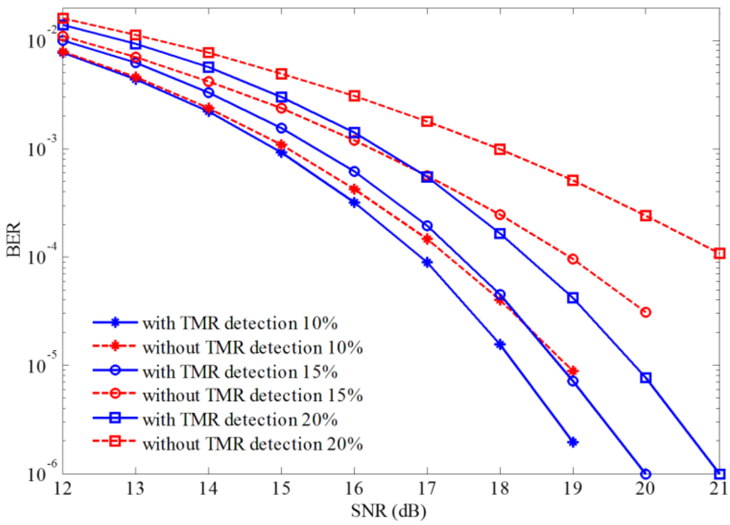

Figure 3 The performance of the proposed equalization system with and without TMR detection and correction method.

the TMR level. According to the empirical results, the proposed mechanism can estimate accurately the TMR level starting from the 10% and up. To correct affected TMR in the system, the proposed technique replaces the target **G** and its equalizer **f** that are tuned with the current TMR level.
In this work, we assume that four pairs of the trellis and the equalizer for the channel experienced with TMR level 0%, 10%, 15%, and 20% are designed in advance using the method from previous section. After the TMR is detected and estimated based on the empirical threshold values, the proposed system will select the appropriate trellis in Viterbi detector and its matched equalizer to replace.

4. Simulation results and discussion

In this paper, we considered a BPMR system with high ADs of 2.5 and the bit period and track pitch are 16 nm, the along-track PW_{50} is 19.4 nm, and the cross-track PW_{50} is 24.8 nm similar to [5]. A signal-to-noise ratio (SNR) is defined as $SNR = 20\log(1/\sigma)$in decibel (dB), where σ is the standard deviation of the AWGN. Firstly, we study the performance of the proposed equalization method with the BPMR system experienced at various TMR levels. In Figure 2, the curve of "Proposed Equ." Represents our proposed equalization method in [5] and "joint-track Equ." represents the joint-track equalization in [4] and the results show that the proposed method provides a performance gain of about 0.3~0.4 dB over the joint-track equalization at the BER of 5×10^{-5}, for all TMR levels but the performance is getting closer when TMR level is higher because the impact of ITI is getting more severe which results in degrading the performance of the detector. The performance of proposed TMR detection and correction mechanism is studied comparing with the system without TMR correction mechanism from [5] for BPMR system in Figure 3. Note that, there is no TMR during the first 100 data sequence in both systems but starting from 101 data sequences, the channel is affected by specific TMR and the proposed method can detect the level of TMR and correct the equalizer and target based on the estimated TMR level. As shown in Figure 3, the performance of the proposed technique yields the significant performance gain over the system without TMR detection.

5. Conclusion

This paper proposes the TMR detecting and estimating method by observing the changes of two consecutive sequences' MSEs which is computed between the equalized signal and the feedback signal from the detector after passing through the one-dimensional (1D) target for a BPMR system corrupted by AWGN and, inter-symbol interference and inter-track interference. Based on the estimated TMR level, the appropriate pair of equalizer and target are selected to tackle TMR. The experiment results indicate that the proposed methods can effectively estimate the TMR level, especially in high levels of TMR. Finally, the equalizer by matching the TMR level offer the performance gain over the conventional system for system with high TMR levels.

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