Soft-information flipping scheme based on *a priori* LLRs summation for ultra-high density magnetic recording

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ABSTRACT
Inter-track interference (ITI) is the main problem in high areal density (AD) of magnetic recording systems such as bit-patterned magnetic recording (BPMR) technology thus the ITI avoidance scheme is the way to improve the performance of the recording system. Two-dimensional (2D) modulation codes i.e., the rate-5/6 2D modulation code, was proposed to avoid the severe ITI effect which can successfully improve the system performance when it was considered without the codeword border effect. However, when we have to consider the codeword border effect, some upper and lower tracks cannot avoid ITI because both of them still be interfered from their sidetracks. To improve this weakness, a rate-5/6 2D modulation code was combined with the bit-flipping technique based on the normalization criteria of the two-dimensional soft-output Viterbi algorithm (2D-SOVA). Although, the bit-flipping technique can improve the performance of all tracks; however, the gain optimization is difficult to describe the relationship of the soft-information flipping technique. Therefore, this research proposes a novel of soft-information flipping scheme to describe the bit-flipping technique based on a priori log-likelihood ratios of the rate-5/6 encoding constraint in BPMR system. The simulation results clearly indicate that, at the same user density, the proposed system can provide bit-error-rate performance gain over the other recording systems in both of with and without position jitter noise.

I. INTRODUCTION
To increase an areal density (AD) of the magnetic recording for hard disk drives, the researchers are exploring new recording technologies, such as two-dimensional (2D) magnetic recording (TDMR),1 bit-patterned media recording (BPMR),2,3 heat-assisted magnetic recording (HAMR),4 microwave-assisted magnetic recording (MAMR),5 etc. These technologies deal with the above-mentioned trilemma in various formats. For BPMR technology, each data bit is created in a fixed position, which is called an island, as opposed to a conventional medium, which has the location of grains randomly. While the AD in BPMR system is increased by reducing the space between the neighboring tracks, the inter-track interference (ITI) also becomes significantly one of the major problems.

An ITI effect can severely degrade the performance of ultra-high-density magnetic recording system e.g., BPMR system6,7 as shown in Fig. 1. Although, the 2D modulation code can protect the severe ITI8 which can efficiently improve the overall system performance, it cannot offer the performance gain over the conventional system when the recording system must encounter the ITI from its sidetracks. Then, the bit-flipping technique was proposed to deal with those ITI sidetrack effects using the different of a priori log-likelihood ratios (LLRs) sign8 which focuses on only the characteristic of LLRs’ sign. Then, the normalized soft-information value was also proposed to be a bit-flipping criterion, which can efficiently improve the overall system performance. However, in the previous work,8 we found that the normalized value is so difficult to confirm where an optimal threshold value is in the bit-flipping process.
Therefore, this paper proposes a novel of soft-information flipping scheme to deal with the mentioned shortcoming which leads to improving the bit-error-rate (BER) performance of BPMR system. The relationship between the encoding condition of the rate-5/6 2D modulation code and the LLRs will be utilized for flipping the ambiguous LLRs in another direction before sending to the threshold detector and decoder, respectively. Simulation results indicate that, at the same user density (UD), the new soft-information flipping technique yields BER performance gain over both of the conventional encoded system and the previous bit-flipping technique based on the normalization threshold value.

II. BPMR CHANNEL MODEL

In this study, we consider a discrete BPMR channel model as shown in Fig. 2. The user-bits, $a_k$, is encoded by a rate-5/6 2D modulation code to obtain the recoded bit sequences. The readback signal of the $l$th data bit of the $k$th track can be calculated as

$$ r_{lk} = \sum_{n} \sum_{m} h_{mn} x_{l,m,n} + n_{lk}, $$

where $x_{l,k}$’s are the recorded-bits, $e\{0, \pm 1\}$ represent the middle, upper, and lower tracks, respectively, $h_{mn}$’s are the 2D channel coefficients, $[m, n] \in (0, \pm 1)$, $m$ and $n$ represent the time indices of bit island in the across- and along-track directions, and $n_{lk}$ is an additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2$. In practice, the channel coefficients, $h_{mn}$, can be obtained by sampling the 2D Gaussian pulse response at the integer multiples of a track pitch, $T_z$ and a bit period, $T_c$. $\Delta_x$ and $\Delta_z$ are the along- and across-track location fluctuation (or position jitter), according to below equation

$$ h_{mn} = A \exp\left\{ -\frac{1}{2\Delta^2}\left[\left(\frac{mT_x + \Delta_x}{PW_x}\right)^2 + \left(\frac{nT_z + \Delta_z}{PW_z}\right)^2\right]\right\}, $$

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, $PW_x$ 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 distribution.

At a receiver, the readback signals are generated by three readers and are equalized by a 2D equalizers, followed by the 2D-SOVA detectors to produce the soft-information, i.e., $[\lambda_{k-1}, \lambda_{k,0}, \lambda_{k,1}]^T$. Then, these soft-information will be taken to generate the refined probability LLRs, i.e., $[\lambda_{k-1}', \lambda_{k,0}', \lambda_{k,1}']^T$ in the probability LLRs adjustment technique before sending to the proposed bit-flipping process to generate the improved soft-information, i.e., $[\lambda_{k-1}''', \lambda_{k,0}''', \lambda_{k,1}''']^T$. Then, the hard decision detector is adopted to generate the estimated recorded-bits, $[\hat{x}_{k-1}, \hat{x}_{k,0}, \hat{x}_{k,1}]^T$. Finally, they will be sent to the decoder to decode the estimated user-bits, $\hat{a}_k$.

III. PROPOSED SYSTEM METHOD

To improve BER performance in the multi-track multi-head BPMR system, we propose a bit-flipping technique based on soft-information LLRs of the rate-5/6 2D coding for avoiding ITI situation of sidetracks. We consider the recoded data pattern in each column vector in the form $3 \times 1$ of the constructive ITI (CITI) data patterns that are recorded onto medium, which consists of $[-1 -1 -1]^T, [1 1 1]^T, [1 -1 -1]^T, [-1 1 -1]^T, [1 -1 1]^T, [-1 -1 1]^T, [1 -1 1]^T$, respectively. From these characteristics, the destructive ITI (DITI) of $[-1 -1 1]$ and $[1 -1 1]$ will not be recorded onto the media for avoiding ITI. From these CITI data patterns, we observe that the upper or lower tracks can be easily flipped in the opposite direction due to the ITI effect of sidetracks. For example, the data patterns $[-1 1 1]^T, [1 -1 1]^T, [1 -1 1]^T, [-1 -1 1]^T$ in cross-track direction as

![FIG. 1. A three-track three-head BPMR channel model with the behavior of ITI effect from their sidetracks.](image)

![FIG. 2. Block diagram of the three-track three-head BPMR channel model with the proposed bit-flipping technique that performs together with the rate-5/6 2D modulation code.](image)
depicted as Fig. 1; the bits of upper and lower tracks will be easily changed to [1 1 1] or [-1 -1 -1], respectively. Thus, this work proposes the bit-flipping technique to improve BER performance when the recording system was interfered from their sidetracks. Firstly, we optimize threshold value, \( \alpha \) to improve BER performance when the recording system was interfered from their sidetracks. Firstly, we optimize threshold value, \( \alpha \) of the refined probability LLRs process which can be defined as the gain flipping. Then, we compare the values of the \( \alpha \) and probability LLRs for deciding to flip the soft-information value sign before sending them to the threshold detector and decoder, respectively. The detail can be explained in the following sections.

A. 5/6 modulation code

The rate-5/6 2D modulation code\(^1\) was designed to avoid the destructive ITI in which the encoding process can be briefly described as follows; every 1×5 bits from the user-bits sequence as \( a \equiv [a_k, a_{k+1}, a_{k+2}, a_{k+3}, a_{k+4}] \) will be rearranged to become three recorded-bit sequences as \( x \equiv [x_{k×1}, x_{k+1×1}; x_{k×2}, x_{k+1×2}; x_{k×3}, x_{k+1×3}]^T \) in a matrix form of 3×2 bits. For the decoding process, the estimated user-bit sequence, \( \hat{x} = [\hat{x}_{k×1}, \hat{x}_{k+1×1}; \hat{x}_{k×2}, \hat{x}_{k+1×2}; \hat{x}_{k×3}, \hat{x}_{k+1×3}]^T \) are decoded by the rate-5/6 2D modulation decoder, which employs the same look-up table as proposed in the previous work\(^6\) to determine the estimated user-bits, \( \hat{a} \) as shown in Fig. 2. Here, a pair of 3 symbols from the estimated recorded-bit sequences will be rearranged as \( \hat{a} \equiv [\hat{a}_k, \hat{a}_{k+1}, \hat{a}_{k+2}, \hat{a}_{k+3}, \hat{a}_{k+4}] \). However, the decoding process may operate incorrectly for some data patterns that are inconsistent with the codewords, i.e., \( \hat{x} \neq x \). To solve this problem, therefore, they apply the Euclidean distance\(^8\) concept in the decoder to measure the similarity between \( \hat{x} \) and \( x \). Here, the decoder computes the Euclidean distance of the estimated recorded-bit sequences \( \hat{x} \) for each codeword \( x \).

B. A soft-information flipping

In the bit-flipping process, we start by considering the soft-information values of the upper, middle, and lower data sequences in the column vector form of 3×1 as shown in Fig. 2. Firstly, the signs of all soft-information values obtained from 2D-SOVA\(^s\) will be checked, whenever we found these two sign-patterns, \([+ + +, - - -] \) or \([+ - -, + - +, - + +, - + -] \), these three soft-information values will be calculated for finding the refined probability LLRs value of each track as follows:

\[
\lambda'_{l,j} = \lambda_{l,j} / \sum_{i=1}^{1} \lambda_{i,j},
\]

where \( I \in [-1, 0, 1] \) represents the upper, middle, and lower tracks, respectively. These probability LLRs will then be compared with the threshold value for deciding which soft-information bits should be flipped as shown in Fig. 1. Here, the optimal threshold value, \( \alpha \) is obtained from our investigation which is depended on AD. In this work, we found that \( \alpha = 0.06 \) is the best point and it is given as the optimal threshold value in this study, it reveals that when the probability value of LLRs less than 0.06 the sign of soft-information will be easily changed. For the bit-flipping process, we consider only two soft-information patterns that have the sign according to \([+ + +] \) and \([- - -] \) in the cross-track direction. If we found that the refined probability LLRs value is less than the optimal threshold value, \( \lambda'_{l,j} < \alpha \), then the LLR will be flipped in opposite directions to obtain the refined LLRs, \( \lambda''_{l,j} \) before sending to threshold detector and decoder, respectively. It is important to note that the along- and across-track pulse widths of the 2D Gaussian pulse response are fixed just for this study. The optimal threshold value may be changed when the other 2D Gaussian pulse responses were adopted in the recording system.

IV. RESULTS AND DISCUSSION

We evaluate the BER performances in several systems as follows; “Uncoded System = 2.5 Tb/in\(^2\)” represents the conventional system without coding and bit-flipping technique, “5/6 Coding wo Bit-Flipping = 3.0 Tb/in\(^2\)” represents the coding system without bit-flipping technique, “5/6 Coding w Bit-Flipping I = 3.0 Tb/in\(^2\)” represents the coding system with bit-flipping technique based on normalized soft-information value method\(^4\), and “5/6 Coding w Bit-Flipping II = 3.0 Tb/in\(^2\)” represents the proposed coding system with bit-flipping based a novel probability LLRs technique. Here, the 2D Gaussian pulse response with the along-track PW\(_{0}\) of 19.4 nm and the across-track PW\(_{0}\) of 24.8 nm is considered. In the simulation, signal-to-noise ratio (SNR) is defined as SNR = 20log(1/(\(R\sigma^2\))), where \( R = 5/6 \) is a code rate and \( \sigma \) is a standard deviation of AWGN. We compare the BER performances of the proposed coded system at the various conditions without and with 5% position jitter noise as shown in Fig. 3. For a fair comparison reason, however, it should be compared with the same UD, e.g., UD = AD × R. Therefore, if we consider the system performance at UD = 2.5 Tb/in\(^2\), the proposed coded system should be considered at AD = 3.0 Tb/in\(^2\), while the conventional uncoded system performance should be investigated at AD = 2.5 Tb/in\(^2\).

When we do not consider the effect of position jitter noise, it is clear that the proposed method (5/6 Coding w Bit-Flipping II = 3.0 Tb/in\(^2\)) can provide better BER performance for about 2.0 over the conventional system (Uncoded System = 2.5 Tb/in\(^2\)) at BER = 10\(^{-5}\). Moreover, this novel technique provides better BER performance for about 1.0 dB over the system that uses the normalized soft-information value method\(^4\) (5/6 Coding w Bit-Flipping I = 3.0 Tb/in\(^2\)) at BER = 10\(^{-5}\) and provide the superior performance when compared with the coded system without bit-flipping technique\(^8\) (5/6 Coding wo Bit-Flipping = 3.0 Tb/in\(^2\)). This result indicates that the rate-5/6 modulation code system without flipping bit cannot cancel the ITI effect of all sidetracks as shown in Fig. 3a. Moreover, when the recording system must encounter the effect of position jitter, we will see that the proposed method still provides better BER performance over the other systems as shown in Fig. 3b. It also implies that the optimal threshold value is independent from the effect of position jitter.

This performance can reveal that the probability LLRs technique is better than the normalized soft-information technique\(^4\) because the LLRs values of all tracks are utilized to define the optimal threshold value for the present proposed technique. While the ratio value that is obtained from the normalized soft-information technique\(^4\) only depends on the maximum value of the soft-information. Especially, when the readback signals were interrupted with lower AWGN, we cannot find the difference between all three soft-information sequences which causes the optimal threshold value cannot classify which LLRs should be flipped. However, in this work, we found that the probability of soft-information LLRs obtained
from all three soft-information sequences can significantly improve the performance of the bit-flipping process.

V. CONCLUSION

As we know that the rate-5/6 two-dimensional modulation code should be performed together with the bit-flipping technique for three-track/three-head bit-patterned magnetic recording. To develop the BER performance of the coded recording system, we propose to utilize the encoding constraint of the 2D modulation code to define the criteria in the bit-flipping process. Here, we also propose to use the refined probability LLRs value in our current bit-flipping technique which is the different point from an earlier bit-flipping technique that focuses on only the soft-information value normalization. The soft-information that are obtained from the upper or lower 2D-SOVA detectors will be flipped to another direction when the system observes that the desired data pattern is one of two forbidden data patterns and the minimum value of the refined probability LLRs value is less than the optimal threshold value. Simulation results indicate that the proposed system can provide a better BER performance when compares with our previous bit-flipping technique. Moreover, the result also reveals that the proposed system yields superior performance gain over the conventional recording systems for both with and without position jitter noise.

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REFERENCES

1. P. Robertson et al., in Proc. IEEE Int. Conf. Commun.(ICC’95) 2, 1009–1013 (1995).
2. S. J. Greaves et al., IEEE Trans. Magn. 44, 3430–3433 (2008).
3. Y. Wang et al., IEEE Trans. Magn. 51, 3002611 (2015).
4. M. H. Kryder et al., Proc. IEEE 96(11), 1810 (2008).
5. Y. Shiroishi et al., IEEE Trans. Magn. 45(10), 3816–3822 (2009).
6. C. Warisarn et al., IEICE Trans. Electron. E98-C(6), 528–533 (2015).
7. C. Warisarn et al., AIP Advances 8(1-5), 056509 (2018).
8. W. Bussytrats et al., in Proceedings of Intermag 2018 (2018).
9. S. Nabavi, Ph.D. dissertation, Dept. Elect. Eng., CMU, Pittsburgh, PA, USA (2008).