Soft Information Adjustment Scheme of a Rate-4/5 2D Modulation Code in Bit-Patterned Media Recording Systems

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Abstract: In bit-patterned media recording (BPMR) systems, the readback signal of the desired track is severely interfered from the adjacent tracks, which known as the inter-track interference (ITI). One way to cope this problem is to use the 2-dimensional (2D) coding e.g., a rate-4/5 2D modulation code. Although the rate-4/5 modulation code ensures that the readback signal of the three inner tracks will not be corrupted by severe ITI; however, both the lowermost and the uppermost tracks could still be interfered by the outer tracks, which may lead to some errors in the data recovery process. To improve this shortcoming, we propose the soft-information adjustment scheme to adjust the soft-information before decoding. The relationship of the data encoding condition will be used as a criterion for adjusting the soft-information. Simulation results indicate that the proposed system is better than the conventional system, especially when areal density and/or the position jitter are high.

Keywords: Bit-patterned media recording, Soft-output Viterbi algorithm, Two-dimensional interference.

1. Introduction

Bit-patterned media recording (BPMR) is one of the promising candidates for the next generation of hard disk drive (HDD) technology, which can extend the areal density (AD) up to 4 terabits per square inch (Tb/in^2) [1]. However, there are many challenges must be investigated such as the two dimensional (2D) interference consisting of the inter-symbol interference (ISI) and inter-track interference (ITI) [2]. The severe ITI can degrade the overall system performance significantly if a precaution is not considered to prevent this situation.

In our previous work [3], we propose the constructive ITI (CITI) coding scheme to cope this problem using the log-likelihood ratio (LLR) algebra implementation in Boolean logic mappings, which jointly perform iterative decoding together with a modified 2D soft-output Viterbi algorithm (2D SOVA) detector [4]. This scheme ensures that none of severe ITI can be appear in the reading process. However, after focusing into the readback data, we found that both the lowermost and the uppermost tracks could still be interfered by the outer tracks, which lead to some errors in the data recovery process easily. Therefore, this paper proposes the soft-information adjustment scheme of a rate-4/5 2D modulation code in BPMR systems. The log-likelihood ratio (LLR) obtained from the modified 2D SOVA will be adjusted with the proposed simple soft-information adjuster before sending to soft-CITI decoder. The performance can be significantly improved when the proposed scheme was adopted in the recording system.

2. BPMR Channel Model

A multi-track multi-head BPMR system with the proposed soft-information adjustment scheme is considered in this paper as shown in Fig. 1. A message bit, u_k is encoded with LDPC encoder [5] to obtain the encoded data sequence, a_k, before splitting the encoded data to be 4 data sequences. Then, it is sent to a CITI encoder [4] to produce 5 data sequences before recording them onto a medium.

The readback signal from the k-th data bit on the l-th track is given by

$$r_{k,l} = \sum_n \sum_m h_{m,n} x_{k-m,l-n} + n_{k,l} , \qquad (1)$$

where $x_{k,l}$'s are the recorded bits, $h_{m,n}$'s are the 2D channel response coefficients [1-3], m and n are the time indices of the bit island in the along-track and across-track directions, respectively, and $n_{k,l}$'s are electronics noises modeled as an additive white Gaussian noise (AWGN) with zero-mean and variance σ^2. In this paper, the 2D channel response coefficients can be obtain by sampling the 2D Gaussian pulse response [6] at integer multiples of the bit period and the track pitch, which can be written as

$$h_{m,n} = A \exp\left\{ -\frac{1}{2b^2} \left[\left(\frac{mT_x + \Delta_x}{\mathrm{PW}_x} \right)^2 + \left(\frac{nT_z + \Delta_z}{\mathrm{PW}_z} \right)^2 \right] \right\}, \qquad (2)$$

Where $\{m,n\} \in \{-L, ..., 0, ..., L\}$, $2L+1$ is the length of the 2D Gaussian pulse response, L is an integer which assumed to be 1 for simplify, $A = 1$ is supposed to be the peak amplitude of the 2D Gaussian pulse response, $b = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard deviation of the Gaussian pulse [6,7], PW_{50} is the pulse width at half of its peak value, Δ_x is the across-track location fluctuation (or position jitter [6,7]), Δ_z is the along-track location fluctuation, PW_x is the PW_{50} of the along-track pulse, PW_z is the PW_{50} of the across-track pulse. 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. To retrieve data, the five data track readback sequences, $r_{k,l}$, are equalized by a 2D equalizer and sent into a modified 2D-SOVA detector to produce the 5-track soft information. The 5 sequences of the soft information will be adjusted with the proposed soft-information adjuster before passing them to CITI decoder to obtain the 4-track soft information $\hat{a}_{k,l}$. Then, it will be merged to one track and sent to the iterative LDPC decoder to produce the estimated message sequence $\hat{u}_k$.

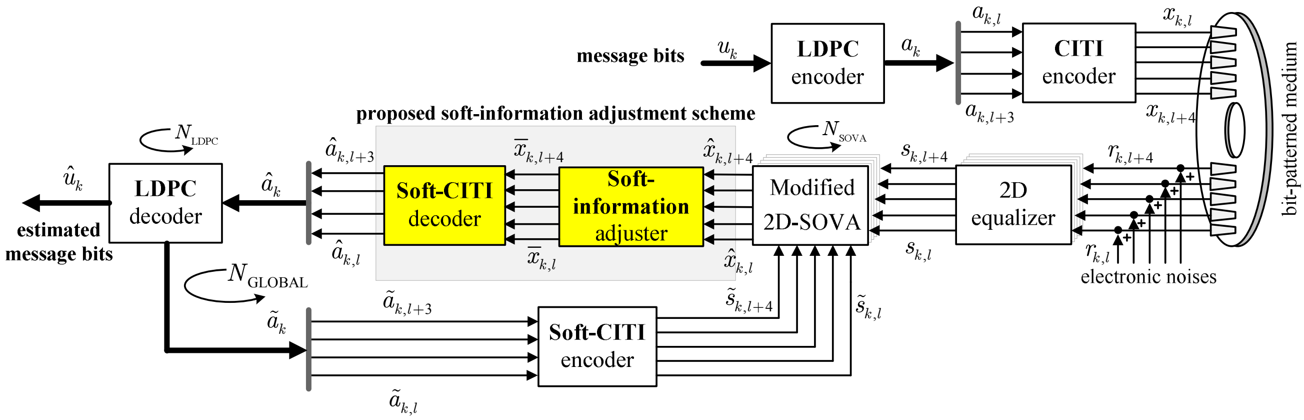

Fig. 1: Block diagram of BPMR systems with the proposed soft-information adjustment scheme.

3. Proposed Scheme

Before recording the data onto the medium, we encode the message bit by using a 4/5 CITI encoder [3]. We shown in our previous work [2,7] that the k-th bit of the adjacent tracks differs from that of the l-th center track could make destructive inter-track interference (DITI) data pattern such as $[-1, 1, -1]^T$ or $[1, -1, 1]^T$, where $[\cdot]^T$ is transpose operator. The 4/5 CITI code could avoid DITI pattern by mapping every 4-by-1 data array $[a_{k,l}, a_{k,l+1}, a_{k,l+2}, a_{k,l+3}]$ to a 5-by-1 codeword $[x_{k,l}, x_{k,l+1}, x_{k,l+2}, x_{k,l+3}, x_{k,l+4}]$ from look-up table as shown in Fig. 2. It is very important to note that these patterns may possibly be changed depending on the considered AD. Nevertheless, we found that the ADs of 2.5 and 3.0 Tb/in^2 have the same DITI patterns. The 4/5 CITI encoder will map all 16 possible input data to be the specific pattern. Hence, the 4/5 CITI encoder scheme can assure that none of DITI pattern could be occur while recording data.

At the receiver, the readback sequences are equalized by a 2D equalizer and are fed to a modified 2D SOVA detectors [4] to produce the 5-track soft information, $\hat{x}_{k,l}$, before passing them to the soft-information adjuster (SIA). Due to the CITI encoder does not allow to record the forbidden data patterns i.e., $[-1\ 1\ -1]^T$ and $[1\ -1\ 1]^T$ onto the medium to avoid the severe ITI situation. Therefore, the SIA will detect all 6 possible patterns from theses soft-information as shown in Fig. 3. If the SIA found that the detected soft-information has similar form with the forbidden data patterns, it will then be defined as a mistake soft-information. We can classify these patterns in each possible type, i.e., Type I–Type VI. Next, the lowest value of soft-information (or its log likelihood ratio (LLR)) among 3 of them will be determined and then inversed as an opposite value. It is very important to note that the LLR value implies its reliability. For example, Type I, the 1st data track is the lowest LLR value in a form $[1\ -1\ 1]^T$; therefore, its 1st track LLR value will be reversed to be the negative LLR value i.e., $[-1\ -1\ 1]^T$.

After these soft-information were adjusted accordingly, the updated soft-information will be sent to the soft CITI decoder [4] to obtain the 4-track soft-information before grouping as the estimated encoded sequence. This sequence will then be passed to LDPC decoder to find the best soft-information. Then, this soft information will be grouped and sent back to the soft CITI encoder to generate the new soft information for each corresponding 2D SOVA detector in the next global iteration, N_{GLOBAL} as shown in Fig. 1. At the last global iteration, the soft information from LDPC decoder will be decided to be hard output as an estimated input sequence $\hat{u}_k$.

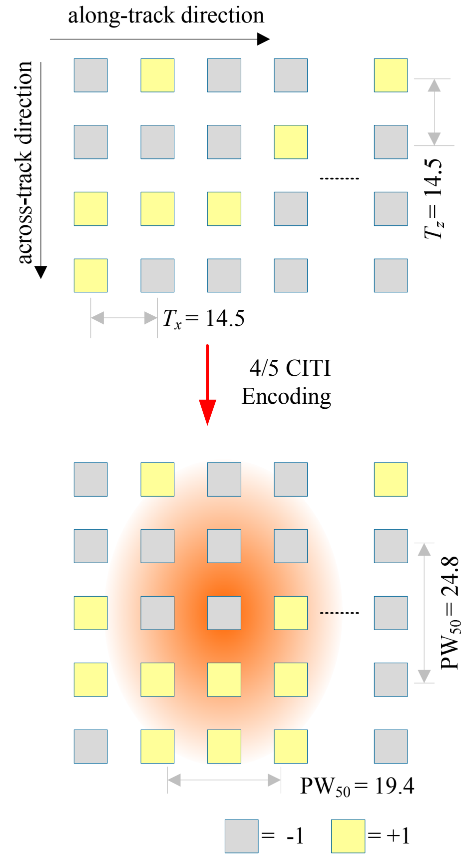

Fig. 2: An 4/5 2D CITI modulation encoding scheme. There are all 16 possible input data patterns will be mapped to be the specific pattern to avoid the destructive inter-track interference (DITI) data pattern before recording the data onto the medium.

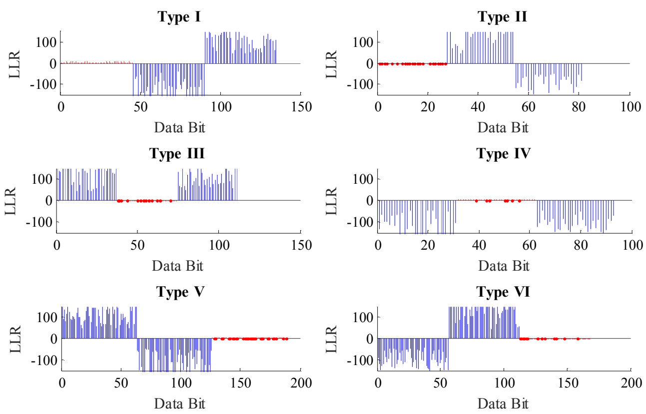

Fig. 3: The examples of soft-information, which obtained from 3 successively data sequences of the modified 2D-SOVA [4] before adjusting with the proposed soft-information adjuster.

4. Results and Discussions

We compare the system performance between 1) the conventional system, which use only a hard 4/5 2D CITI modulation code and conventional Viterbi algorithm, this system denotes as "Uncoded", 2) the system which use a rate-4/5 2D CITI modulation code performed together with SOVA algorithm denoted as "Conventional scheme [3]", and 3) our proposed scheme, which use a rate-4/5 2D CITI modulation code performed together with the proposed soft-information adjuster and SOVA algorithm denoted as "Proposed scheme". The iteration numbers of N_{SOVA}, N_{LDPC}, and N_{GLOBAL} are defined to be 3, 4, and 5 iterations, respectively.

We consider the BPMR channel in Fig. 1 at the AD of 3.0 Tb/in^2 (T_x= T_z = 14.5 nm), where the along-track PW$_{50}$ is 19.4 nm, and the across-track PW$_{50}$ is 24.8 mm, similar to [3,7]. Then, we define signal-to-noise ratio (SNR) as

$$\mathrm{SNR} = 10\log_{10}\left(\frac{1}{\mathrm{R}\sigma^2}\right), \quad (3)$$

in decibel (dB), where "1" is assumed to be the peak amplitude of the readback signal, and R is an overall code rate of the system i.e., R = 0.8. In this paper, the 2D 3-by-3 symmetric target and its corresponding 2D 3-by-7 equalizer are designed based on a minimum mean-squared error approach [8] which given as

$$\text{2D Target} = \begin{bmatrix} 0.02 & 0.20 & 0.02 \\ 0.10 & 1.00 & 0.10 \\ 0.02 & 0.20 & 0.02 \end{bmatrix}, \quad (4)$$

Fig. 4 compares the bit-error rate (BER) performance between the different systems at the AD of 3.0 Tb/in^2 without position jitter, i.e., σ_j/T_x = 0. Clearly, the performance of our proposed scheme yields slightly better than conventional scheme [3] of about 0.4 dB at BER = 10^{-4} and the proposed scheme has superior performance over the uncoded system of about 4 dB at BER = 10^{-4}.

In additional, we further compare the performance between the proposed system and the conventional 2D CITI modulation code [3]. The performance is compared through the position jitter versus the SNR requirement to achieve the BER of 10^{-4} at the AD of 3.0 Tb/in^2 , which track pitch and bit length are given 14.5 nm [3,7]. In Fig. 5, it is clear that the proposed scheme is better than the conventional one [3], especially when the position jitter is high. For example, the proposed scheme requires the lower SNR than the conventional one around 0.3 and 0.4 dB at the position jitters of 0% and 5%, respectively, to achieve the BER of 10^{-4}.

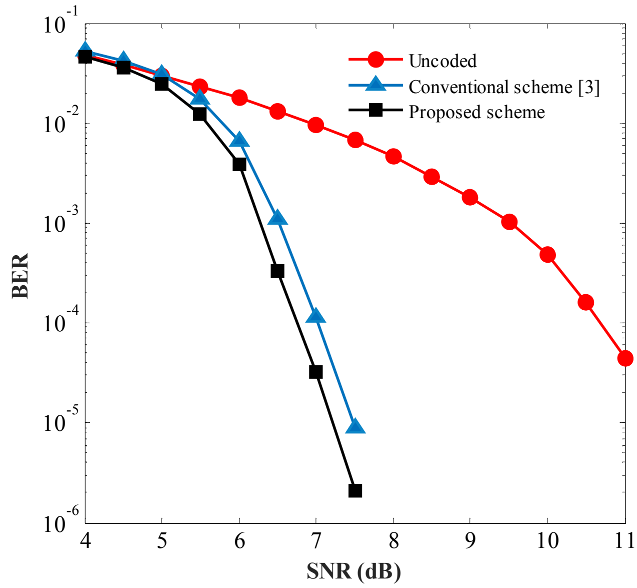

Fig. 4: Performance comparison of different approaches at different signal-to-noise ratio (SNR) amounts without position jitter at AD equals to 3.0 Tb/in^2.

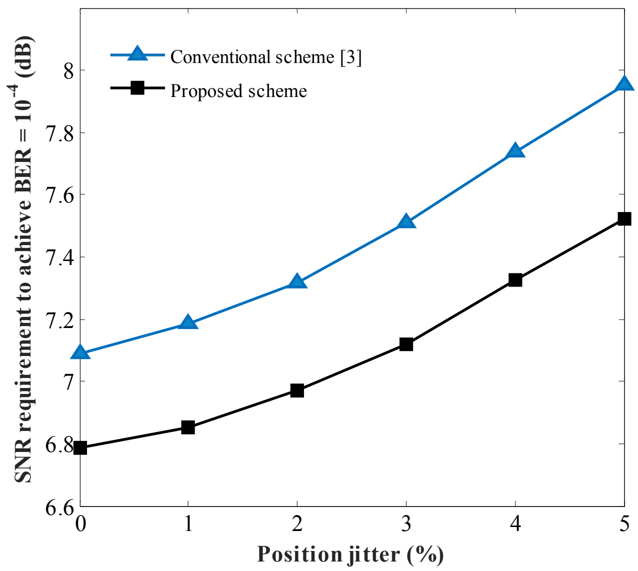

Fig. 5: Performance comparison of different approaches at different position jitter amounts from 0% to 5% at AD equals to 3.0 Tb/in^2. The iteration numbers of N_{SOVA}, N_{LDPC}, and N_{GLOBAL} are defined to be 3, 4, and 5 iterations, respectively.

5. Conclusion

This paper proposes the soft-information adjustment technique, which performs together with the rate-4/5 CITI modulation code in BPMR systems. The relationship of the data encoding condition is utilized as a criterion for adjusting the soft-information before decoding process. The system performance can be significantly improved when the proposed scheme is adopted in recording systems, especially if the position jitter is high.

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