# A Simple Crossover-based Coding Technique for ITI Mitigation in Bit-Patterned Media Recording

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***Abstract*—Due to bits being recorded at ultra-high density, a bit-patterned media recording (BPMR) system is faced with two-dimensional (2D) interference, namely inter-symbol interference (ISI) and inter-track interference (ITI), which degrades the overall performance of a recording system. One solution to avoid the 2D interference effect is to apply a modulation code to forbid some specific data patterns leading to severe 2D interference. Nonetheless, this method usually requires either many redundant bits or additional memory. Thus, this paper proposes a simple technique to encode an input data sequence to mitigate the 2D interference effect before recording them onto a magnetic medium. The proposed technique shows the improvement in reducing complexity and additional memory using a crossover-based technique when comparing to other existing methods.**

## I. Introduction

Conventional magnetic recording technologies for hard disk drive (HDD) are approaching the recording density limit. One of new technologies for increasing an areal density (AD) in HDD is bit-patterned media recording (BPMR) [1-3]. To increase an AD in BPMR; however, the spacing between data bit islands in both the along-track and the across-track directions must be reduced, thus increasing the two-dimensional (2D) interference. This 2D interference consists of inter-track interference (ITI) and inter-symbol interference (ISI), which degrades the performance of a magnetic recording system. Then, one must take care of the 2D interference effect so as to achieve a high-density BPMR system.

Many 2D coding schemes[4-5] have recently been proposed to alleviate the 2D interference. However, these 2D coding schemes were designed based on the channel model with overshoot, and only investigated the worst case scenario of the recorded bit patterns. For example, the 2D coding scheme with a code rate of 7/9 was specially designed in [4] to avoid the destructive case, where the redundant bits were placed in fixed positions at every $3 \times 3$ data array. Nonetheless, this coding scheme had a disadvantage that the redundant bits had no error correction ability. Then, Shao *et al.* [5] presented a rate-5/6 2D coding scheme, which had lower redundancy and yielded better performance than the code in [4]. Recently, Arrayangkool *et al.* [6] introduced a recorded-bit patterning (RBP) scheme to combat the 2D interference, but it had high complexity and required large buffer memory. Therefore, our proposed coding scheme was introduced to tackle the 2D interference effect based on a crossover technique, which not only has lower complexity but also uses less additional buffer memory.

The rest of this paper is organized as follows. After describing a BPMR channel model in Section II, Section III explains how the proposed coding technique performs. Simulation results and complexity comparison are given in Section IV. Finally, Section V concludes this paper.

## II. Channel Model

Consider a multi-track multi-head BPMR system [6] with the proposed coding schemes in Fig. 1. Three input sequences $\{a_{k,l},\ a_{k,l+1},\ a_{k,l+2}\} \in \{\pm 1\}$ with bit period $T_x$ are encoded by the proposed encoder to obtain three data tracks $\{x_{k,l}, x_{k,l+1},\ x_{k,l+2}\}$ before recording them onto a medium. The readback signal from the *k*th data bit on the *l*th track can be written as [3,6]

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

where $x_{k,l}$'s are the recorded bits, $\otimes$ is a 2D convolution operator, $h_{m,n}$'s are the 2D channel response coefficients [3,6], *m* and *n* are the time indices of the bit island in the along-track and the across-track directions, and $w_{k,l}$ is an additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2$.

Practically, the 2D channel response coefficients are given by $h_{m,n} = P(mT_x, nT_z)$ [6], where $P(x,z)$ is a 2D Gaussian pulse response, *x* and *z* are the time indices in the along-track and the across-track directions, $\{m, n\} \in (-L, \ldots, 0, \ldots, L)$, $2L+1$ is the length of $P(x,z)$, and *L* is an integer.

For simplicity, we use *L* = 1 to guarantee that the tail amplitude of $P(x,z)$ is small. Additionally, this paper considers the 2D Gaussian pulse response of the form [1]

$$P(x,z) = A \exp\left\{ \left[ -\frac{1}{2c^2}\left(\frac{x+\Delta_x}{\mathrm{PW}_x}\right)^2 + \left(\frac{z+\Delta_z}{\mathrm{PW}_z}\right)^2 \right] \right\}, \tag{2}$$

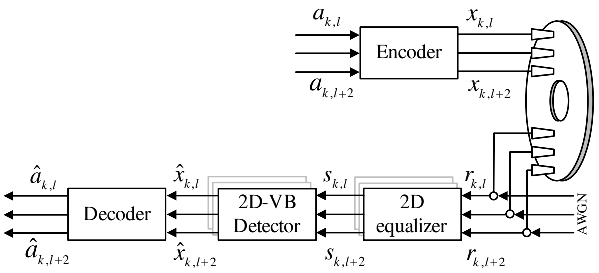


Fig. 1. A BPMR channel model with the proposed coding scheme.

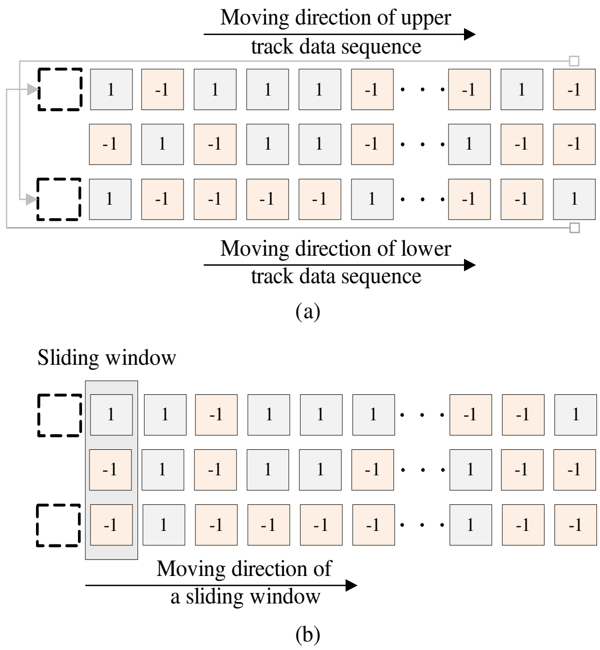


Fig. 2. The proposed coding scheme performs two processes consisting of (a) the data crossing and (b) the DITI pattern counting processes.

where $A$ = 1 is assumed to be the peak amplitude of the pulse response, $c$ = 1/2.3548 is a constant to account for the relationship between $\mathrm{PW}_{50}$ and the standard deviation of a Gaussian pulse [1], $\Delta_x$ is the along-track location fluctuation (or position jitter [1,3], $\Delta_z$ is the across-track location fluctuation, $\mathrm{PW}_x$ is the $\mathrm{PW}_{50}$ of the along-track pulse, and $\mathrm{PW}_z$ is the $\mathrm{PW}_{50}$ of the across-track pulse. Here, we assume that the position jitters ($\Delta_x$ and $\Delta_z$) are modeled as a truncated Gaussian probability distribution function with zero mean and $\sigma_j^2$, where $\sigma_j$ is specified as the percentage of $T_x$.

At the receiver, the readback data sequence $r_{k,l}$ is equalized by a 2D equalizer to obtained a sequence $s_{k,l}$, and is then sent to the 2D Viterbi detector [1,3] to determine the most likely recorded sequence $\hat{x}_{k,l}$. Finally, the proposed decoder is employed to decode the three-track data sequence $\hat{x}_{k,l}$ to obtain an estimated input data sequence $\hat{a}_{k,l}$.

## III. Proposed Coding Scheme

Generally, the 2D interference has an effect on the detected bit. The effect can be either constructive or destructive, depending on the readback waveform of the detected bit and its surrounding bits [6]. By comparing between the signal amplitude of a single isolated bit and that of a center bit of a $3 \times 3$ data pattern, the constructive or destructive interference will amplify or decrease its signal amplitude. Hence, when the readback signal of the detected bit encounters the destructive interference; its signal amplitude will be small, thus making it difficult to detect the desired bit correctly.

In RBP scheme [6], we found that all destructive patterns consisted of the $[1, -1, 1]^{\mathrm{T}}$ or $[-1, 1, -1]^{\mathrm{T}}$ patterns occurring at the center bit position, $[\cdot]^{\mathrm{T}}$ is a transpose operator. In this paper, we define $[1, -1, 1]^{\mathrm{T}}$ or $[-1, 1, -1]^{\mathrm{T}}$ as a destructive inter-track interference (DITI). Therefore, we propose a simple coding scheme to avoid this DITI by rearranging the data sequence based on a crossover technique to prevent some specific data patterns that might lead to DITI patterns.

### A. Encoding Process

The detail on how the proposed coding scheme works can be explained as follow. We consider the three track data sequences, which will be referred to as the upper, the center, and the lower tracks. Thus, the proposed encoding scheme performs into 2 steps, consisting of *data crossing* and *DITI pattern counting* processes.

In the data crossing process, the center track will be fixed. Then, at each the *i*th iteration, the last bit in the upper track will be placed at the beginning of the lower track, while the last bit in the lower track will also be placed at the beginning of the upper track as shown in Fig. 2(a). After that, both the upper and the lower data sequences will be circularly shifted one bit to the right before proceeding to the DITI pattern counting process.

In the DITI pattern counting process, we define a sliding window of a $3 \times 1$ array that covers 3 bits, i.e., one bit from the upper track $a_{k,l}$, one bit from the center track $a_{k,l+1}$, and one bit from the lower track $a_{k,l+2}$ as demonstrated in Fig. 2(b). This sliding window will be moved from the beginning to the end of the center track to search for the DITI pattern. When the sliding window detects the DITI pattern, the DITI pattern amount will be increased. Then, the total number of detected DITI patterns at each the *i*th iteration of the data crossing process will be kept and compared with that at other iterations.

The encoding scheme will perform these two processes for *N* iterations, where *N* is the data sequence length of each track. Then, the *i*th iteration that yields the smallest number of detected DITI patterns will be kept in an additional memory for using in the decoding process, whereas the data pattern of the *i*th iteration will be the best data pattern that will be recorded onto a magnetic medium.

For calculating the complexity of the proposed encoding scheme, we consider the Big-O notation comparison which can be calculated by multiplying the maximum number of iteration, *N* with number of moving times of sliding window

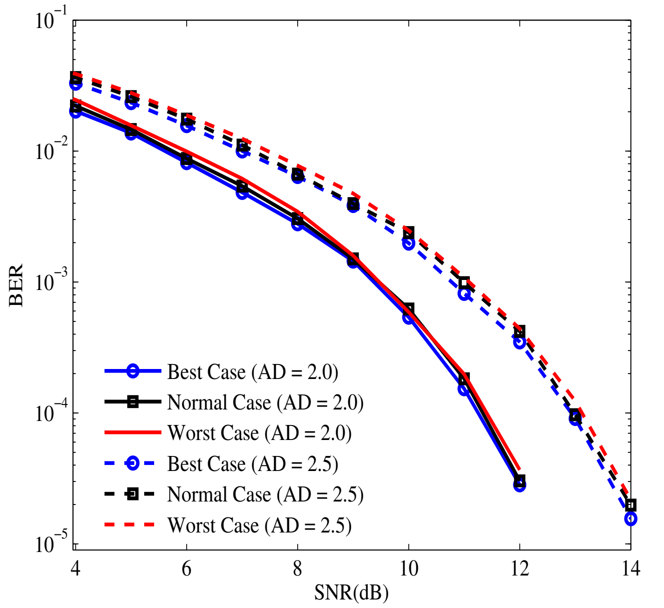


Fig. 3. BER performance at areal density equal to 2.0 and 2.5 Tb/in$^2$ with $\sigma_j$ = 0% position jitter.

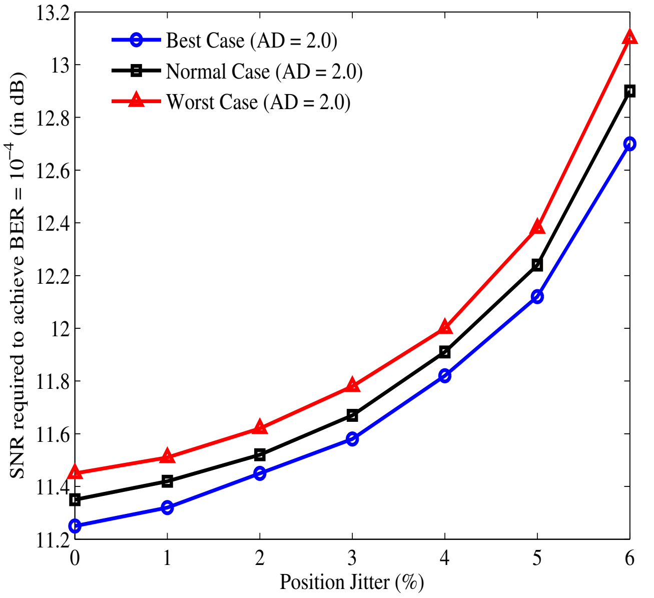


Fig. 4. Performance comparison of different schemes at different position jitter amounts at areal density of 2.0 Tb/in$^2$.

(which is also equal to *N*). Therefore, the complexity can be calculated as

$$\text{complexity} = \mathrm{O}(N^2), \tag{3}$$

where $\mathrm{O}(\cdot)$ is the Big-O notation, while the RBP [6] provided the complexity of about $\mathrm{O}\left(N^3\right)$. It is clear that our proposed scheme has lower complexity than the RBP one.

### *B. Decoding Process*

The decoding process will perform similar to the encoding (data crossing) process, but in an opposite way. The number of iterations used in the encoding process that provides the best data pattern, e.g., $i$ iterations, will be employed at this time. Specifically, at each iteration, the first bit of the lower track will be placed after the last bit of the upper track, while the first bit of the upper track will be placed after the last bit of the lower track. The decoding scheme will perform in this manner for $i$ iterations, where $i$ is obtained from the buffer memory.

## IV. Simulation Results

In this experiment, we test the proposed coding technique by using $3 \times 4096$ bits for each data stream and define the signal-to-noise ratio (SNR) from 4 to 14 dB. This paper focuses on the performance comparison among 1) the best case representing the system with the proposed method that yields the minimum number of DITI, 2) the normal case representing the system without any coding scheme, and 3) the worst case representing the system with the proposed method that yields the maximum number of DITI.

A SNR is defined as

$$\text{SNR} = 20\log_{10}\left(1/\sigma\right), \tag{4}$$

in decibel (dB), where $\sigma$ is a standard deviation of AWGN. The 2D $3\times3$ target and 2D $3\times7$ equalizer are designed based on a minimum mean square error (MMSE) approach [1-3] at the SNR required to achieve bit-error rate (BER) of $10^{-4}$. In simulation, each BER is computed based on a minimum number of 500 error bits, and one data sector consists of 4096 bits.

Fig. 3 shows the BER performance of different schemes for BPMR system at areal densities equal to 2.0 and 2.5 Tb/in$^2$ with $\sigma_j$ = 0% position jitter (without position jitter). The curves labeled as "Normal Case", "Best Case", and "Worst Case" represent the regular case (i.e., recording random bits), the recorded bits were patterned based on our proposed scheme, and the worst case (i.e., the most occurring of the worst patterns), respectively. Clearly, the "Best Case" performs better than both the "Normal Case" and "Worst Case" without position jitter.

In addition, when the areal density is increased from 2.0 Tb/in$^2$ to 2.5 Tb/in$^2$, the "Best Case" still provides better performance than the others, and yields about 0.3 dB and 0.4 dB gain at BER = $10^{-4}$ over the "Normal Case" and the "Worst Case", respectively. This is because the proposed technique will always change any bad data pattern into the best one before recording the best data pattern onto the medium.

We also compare the performance of different schemes at various position jitter amounts in Fig. 4, by plotting the SNR required to achieve BER = $10^{-4}$ as a function of position jitter noise amounts. It is apparent that the "Best Case" is still better than other schemes through all the position jitter amounts.

## V. Conclusions

This paper proposed the simple coding scheme based on crossover technique for solving a destructive inter-track interference (DITI) problem in bit-patterned magnetic recording (BPMR) system to encode an input data sequence to mitigate the 2D interference effect before recording them onto a magnetic medium. The simulation result shows that the proposed method can slightly improve the system performance for all of position jitter levels with low complexity and additional memory. In near future, the proposed technique will be split the data sequence into a small portions which help improve the system performance and reduce the processing time.

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