A Coding Scheme Using Redundant Bits for Bit Patterned Media Recording Channel without Overshoot

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***Abstract*— In bit patterned magnetic recording (BPMR), The two-dimensional (2D) interference composed of inter-symbol and inter-track interference is a major problem especially at high areal density (AD). One way to alleviate the destructive effect of 2D interference is to deploy a 2D coding scheme on an input data sequence before recording in order to avoid some data patterns that easily cause an error at the data readback process. However, some coding schemes generate high complexity. Consequently, this paper proposes a new low-complexity modulation code with redundant bits to eliminate the data patterns leading to severe 2D interference and compare overall system performance. Experimental results indicate that the system with the proposed code is superior to that without coding, especially when the AD is high and/or the position jitter is large.**

I. INTRODUCTION

Bit-patterned media recording (BPMR) is one of the candidates for future ultrahigh density magnetic storage beyond 1 Tbit/in^2 [1-3]. In BPMR, each bit is recorded on a single domain magnetic island and the areal density is increased by reducing the spacing between adjacent islands in along-track and cross-track directions. The read-back signal amplitude is increased or reduced by two dimensional (2-D) interference consisted of inter-symbol interference (ISI) and inter-track interference (ITI), and generate either constructive or destructive effect which degrades the performance of the data recovery channel.

In order to reduce the destructive 2-D interference and improve detection accuracy, modulation codes are usually introduce to constrain the signal patterns in the time domain or space domain, to forbid certain patterns that are more likely to be corrupted by the channel. Several 2D coding schemes [4-10] have recently been proposed for coding the data. For example, a rate-7/9 2D coding scheme was introduced [4] to avoid the severely destructive interference by placing the redundant bits in fixed positions at every 3-by-3 data array. Nonetheless, its drawback is that the redundant bits have no error correction capability. Then, Shao et al. presented a rate-5/6 2D coding scheme [6], which had lower redundancy and yielded better performance than the rate-7/9 one. However, these coding schemes with redundant bit is proposed only in BPMR channel with overshoot. In addition, a rate 4/6 modulation code [7] was introduced to remove the fatal 2D ISI patterns in holographic data storage. Recently, Arrayangkool et al. [8-9] proposed a recorded-bit patterning (RBP) scheme to avoid the destructive 2D interference by shifting method. Additionally, M-RBP [10] was proposed to significantly improve BER performance of the RBP by using weight decision. However, it had high complexity and required large buffer memory.

This paper focuses only on how to handle the destructive 2D interference in BPMR channel without overshoot. In the detected bit can be either destructive or constructive, depending on the readback waveform of the detected bit and its surrounding bits [6]. Specifically, given signal amplitude of an isolated bit, the destructive/constructive 2D interference will decrease/amplify its signal amplitude. As a result, when the readback signal of the detected bit encounters the destructive 2D interference, it could easily cause an error at the data recovery process. To combat the destructive 2D interference, we propose the 3/4 modulation coding scheme. Specifically, the proposed modulation encoder converts 3-track input data (user bits) sequence into 4-track channel bit sequences based on filling redundant bits before recording onto a magnetic medium. These coding schemes can avoid some fatal destructive 2D interference patterns before recording into media. Consequently, the BPMR readback signal will not be corrupted by the severe destructive effect, thus improving the data recovery process.

II. CHANNEL MODEL

Consider a multi-track multi-head BPMR system [8-10] with a proposed coding scheme in Figure 1. A 3-track binary input sequence $a_{k,l} \in \{\pm 1\}$ with bit period T_x is encoded by an proposed encoder to obtain four data tracks $\{x_{k,l}, x_{k,l+1}, x_{k,l+2}, x_{k,l+3}\}$ before recording them onto a medium. The readback signal from the k^{th} data bit on the l^{th} track can be written as

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

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], 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 σ^2. In BPMR,

$h_{m,n}$'s can be obtained by sampling the isolated island pulse response at integer multiples of the bit period T_x and the track pitch T_z, i.e.,

$$h_{m,n} = P\left(-mT_x, -nT_z\right), \quad m,n \in \left(-L,0,L\right), \tag{2}$$

where $P(x, z)$ is the 2D Gaussian pulse response, x and z are the time indices in the along-track and the across-track directions, $\{m, n\} \in (-L, ..., 0, ..., L)$, $2L+1$ is the length of $P(x, z)$, and L is an integer. In general, L should be large enough to ensure that the tail amplitude of $P(x, z)$ is small (here, we use $L = 1$ for simplicity). Additionally, this paper considers the 2D Gaussian pulse response of the form [3]

$$P(x,z) = A\exp\left\{-\frac{1}{2c^2}\left[\left(\frac{x+\Delta_x}{\mathrm{PW}_x}\right)^2 + \left(\frac{z+\Delta_z}{\mathrm{PW}_z}\right)^2\right]\right\}, \tag{3}$$

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 PW_{50} and the standard deviation of a Gaussian pulse [3], Δ_x is the along-track location fluctuation (or position jitter [8-10]), Δ_z is the across-track location fluctuation, PW_x is the PW_{50} of the along-track pulse, and 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 σ_j^2, where σ_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 [3] to determine the most likely recorded sequence $\{\hat{x}_{k,l}\}$. Finally, a proposed decoder is employed to decode the 4-track data sequence $\{\hat{x}_{k,l}\}$ into a 3-track data sequence of an estimated input data sequence $\hat{a}_{k,l}$.

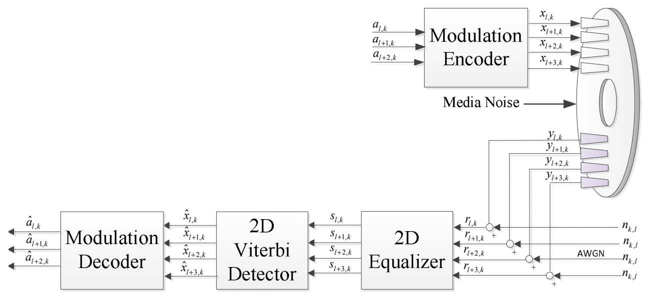

Fig. 1 System Block Diagram

III. Proposed Coding Schemes

By analyzing all destructive data patterns in RBP [8], we found that most of them are occurred when the k^{th} bit of the adjacent tracks differ from that of the center track, i.e., $[a_{k,l-1}, a_{k,l}, a_{k,l+1}]^T = [1\ -1\ 1]^T$ or $[-1\ 1\ -1]^T$. Hence, we use this result to design our coding schemes to avoid such destructive data patterns to be written onto a medium. Here, we propose the ITI-mitigating 3/4 modulation coding schemes for a multi-track multi-head BPMR system. The encoding and decoding processes are performed based on the filling and removing redundant bits. The proposed modulation encoder converts 3-track input data (user bits) sequences $\{a_{k,l}\}$, $\{a_{k,l+1}\}$, $\{a_{k,l+2}\}$, into 4-track code words, $\{x_{k,l}\}$, $\{x_{k,l+1}\}$, $\{x_{k,l+2}\}$, and, $\{x_{k,l+3}\}$ as in Figure 2.

In the encoder process, the 3-track input data (user bits) sequences $\{a_{k,l}\}$, $\{a_{k,l+1}\}$, $\{a_{k,l+2}\}$ will be changed to 4-track channel bits sequences, $\{x_{k,l}\}$, $\{x_{k,l+1}\}$, $\{x_{k,l+2}\}$, and $\{x_{k,l+3}\}$ by repeating $a_{k,l+1}$ bit as shown in Table 1. The redundant bit $x_{k,l+2}$ is absolutely equal to $a_{k,l+1}$ and $x_{k,l+1}$ in order to avoid the DITI patterns. On the other hand, the modulation decoder will remove the redundant bit $\hat{x}_{l+2,k}$ and bring $\{x_{k,l}\}$, $\{x_{k,l+1}\}$, and $\{x_{k,l+3}\}$ to be $\hat{\mathbf{a}}$.

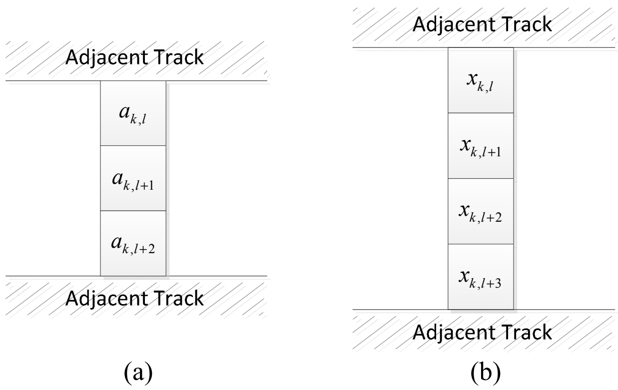

Fig. 2 User bits (a) and Code words (b)

Table I

List of User Bits and Code Words

User bits, $\mathbf{a}$			Code words, $\mathbf{x}$			
$a_{k,l}$	$a_{k,l+1}$	$a_{k,l+2}$	$x_{k,l}$ $\{a_{k,l}\}$	$x_{k,l+1}$ $\{a_{k,l+1}\}$	$x_{k,l+2}$ $\{a_{k,l+1}\}$ (redundant bit)	$x_{k,l+3}$ $\{a_{k,l+2}\}$
-1	-1	-1	-1	-1	-1	-1
-1	-1	1	-1	-1	-1	1
-1	1	-1	-1	1	1	-1
-1	1	1	-1	1	1	1
1	-1	-1	1	-1	-1	-1
1	-1	1	1	-1	-1	1
1	1	-1	1	1	1	-1
1	1	1	1	1	1	1

IV. Simulation Results

We test the proposed coding scheme in the BPMR system, where the two outer tracks (l-1) and (l+4) contain random data. For the conventional system (no coding), an input sequence a_k is written into a single track with random data on adjacent tracks. The signal-to-noise ratio (SNR) is defined as $10\log_{10}(1/R\sigma^2)$ in dB, where $R = 3/4 = 0.75$ is a code rate and σ is a standard deviation of AWGN. The 2D 3-by-3 target and 2D 3-by-7 equalizer are designed based on a minimum mean-squared error (MMSE) approach [1,3] at the SNR required to achieve the bit-error rate (BER) of 10^{-4}, where the 2D Viterbi detector for this 3-by-3 symmetric target employs the trellis having 36 states with 6 parallel branches between any two connected states [3]. In simulation, each BER is computed based on a minimum number of 500 erroneous bits, and one data sector consists of 4096 bits.

We consider the high ADs of 2.5 and 3.0 Tb/in^2 which correspond the bit period, T_x and track pitch, T_z are 16 nm and

14.5 nm, respectively. The along-track PW_{50} is 19.4 nm, and the across-track PW_{50} is 24.8 nm, similar to that considered in [1,3]. Fig. 3 compare the BER performance of the system with and without proposed coding scheme at the ADs of 2.5 and 3 Tb/in^2 without position jitter (i.e., σ_j = 0%). It is evident that the system with our proposed coding outperforms that without coding. Specifically, at BER = 10^{-4}, the proposed coding scheme can provide about 2 dB gain at 2 Tb/in^2 and is far superior to that of without coding at 3 Tb/in^2.

We also compare the performance of different schemes by plotting the SNR required to achieve BER = 10^{-4} as a function of position jitter amounts in Fig. 4. Clearly, the system with proposed coding is superior to that without any coding, especially when the position jitter is large. Thus, the proposed coding scheme is worth employing in the BPMR system.

V. Conclusions

In high-density BPMR, the ISI and ITI can be considered as a major cause of performance degradation. Because some weak 2D Interference patterns can be handled by equalization, this paper focuses only on mitigating the severe 2D Interference, and then proposes the 3/4 modulation code. The key idea is to insert the redundant bits to prevent all data pattern that easily causes an error at the data recovery process to be recorded onto a magnetic medium. Simulation results show that the system with our proposed coding can provide a large performance gain if compared to that without coding, especially when an areal density is high and/or the position jitter is large. Moreover, we will improve the coding method in an aspect of error correction ability in the near future.

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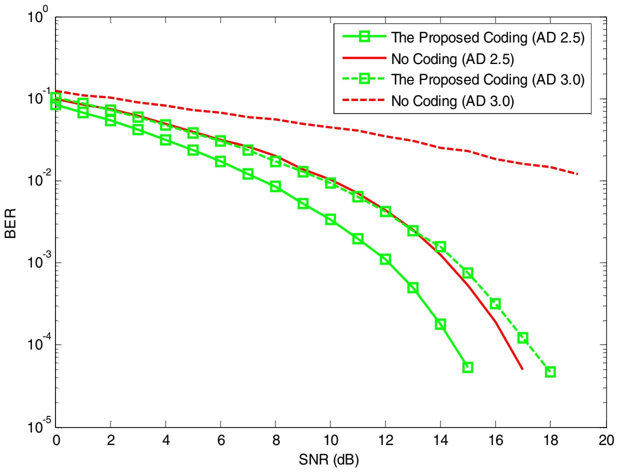

Fig. 3 BER performance at different areal densities without position jitter

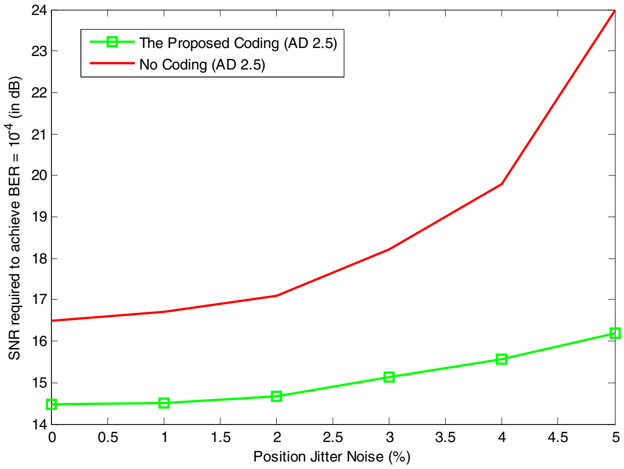

Fig. 4 Performance comparison for various position jitter amounts at AD = 2.5 Tb/in^2.

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