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A constructive inter-track interference coding scheme for bit-patterned media recording system

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The inter-track interference (ITI) can severely degrade the system performance of bit-patterned media recording (BPMR). One way to alleviate the ITI effect is to encode an input data sequence before recording to avoid some data patterns that easily cause an error at the data detection process. This paper proposes a constructive ITI (CITI) coding scheme for a multi-track multi-head BPMR system to eliminate the data patterns that lead to severe ITI. Numerical results indicate that the system with CITI coding outperforms that without CITI coding, especially when an areal density (AD) is high and/or the position jitter is large. Specifically, for the system without position jitter at bit-error rate of 10^{-4}, the proposed scheme can provide about 3 dB gain at the AD of 2.5 Tb/in.^{2} over the system without CITI coding. [http://dx.doi.org/10.1063/1.4855955]

I. INTRODUCTION

To achieve high areal density (AD) in bit-patterned media recording (BPMR), the spacing between bit islands in the along-track and the across-track directions must be reduced, thus leading to the increase of two-dimensional (2D) interference.[1] Practically, the 2D interference consisting of inter-symbol interference (ISI) and inter-track interference (ITI) can deteriorate the system performance considerably if precautions are not taken.

Several 2D coding schemes[2–5] have recently been proposed to cope with the 2D interference in BPMR. For example, a rate-7/9 2D coding scheme was introduced[2] to avoid the 2D interference by placing the redundant bits in fixed positions at every 3-by-3 data array. Shao *et al.*[3] presented a rate-5/6 2D coding scheme, which had lower redundancy and yielded better performance than the previous code.[2] In addition, a rate-4/6 modulation code[4] was introduced to remove the fatal 2D ISI patterns in holographic data storage. Recently, Arrayangkool *et al.*[5] proposed a recorded-bit patterning (RBP) scheme to combat the 2D interference, but it had high complexity and required large buffer memory.

In general, the ITI effect experienced in the detected bit can be either destructive or constructive, depending on the readback waveform of the detected bit and its surrounding bits.[5] Specifically, given a signal amplitude of an isolated bit, the destructive/constructive ITI will decrease/amplify its signal amplitude. As a result, when the readback signal of the detected bit encounters the destructive ITI (DITI), it could easily cause an error at the data recovery process.

To combat the DITI, we propose the constructive ITI (CITI) coding scheme (or a new modulation code). Specifically, an input data sequence is first split into four tracks in which will then be encoded by a CITI encoder based on a look-up table before recording onto a magnetic medium. This coding scheme guarantees that the BPMR readback signal will not be corrupted by the severe ITI, thus facilitating the data recovery process.

II. CHANNEL MODEL

Consider a multi-track multi-head BPMR system[1,6] with a rate-4/5 CITI coding scheme in Fig. 1. A binary input sequence $a_k \in \{\pm 1\}$ with bit period T_x is split into four tracks $\{a_{k,l}\}$, which are then encoded by the CITI encoder to obtain five data tracks $\{c_{k,l}\}$, where $c_{k,l} \in \{\pm 1\}$, before recording them onto a medium. The readback signal from the kth data bit on the lth track can be written as

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

where $c_{k,l}$'s are the recorded bits, $h_{m,n}$'s are the 2D channel response coefficients,[1,7] 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., $h_{m,n} = P(-mT_x, -nT_z)$, 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, $\{m,n\} \in \{-L, \ldots, 0, \ldots, L\}$, $2L+1$ 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,[7]

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

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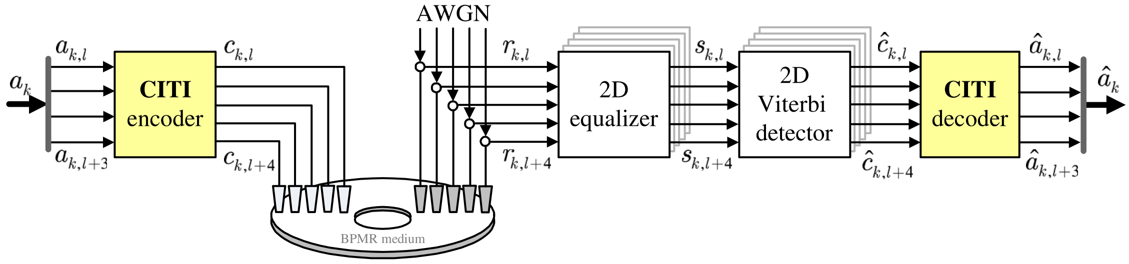

FIG. 1. A channel model with the CITI coding scheme.

where $A = 1$ is assumed to be the peak amplitude of the pulse response, $b = 1/2.3548$ is a constant,[7] Δ_x is the along-track location fluctuation (or position jitter (Ref. 1)), 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. This paper assumes that the position jitters (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.

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[1,6] to determine the most likely recorded sequence $\{\hat{c}_{k,l}\}$. Finally, a CITI decoder is employed to decode the 5-track data sequence $\{\hat{c}_{k,l}\}$ into the 4-track data sequence $\{\hat{a}_{k,l}\}$ before grouping it to obtain an estimated input sequence $\hat{a}_k$.

III. PROPOSED SCHEME

We assume that the read head reads the data at the lth track, and the interference in the cross-track direction is limited to the two adjacent tracks $(l-1)$ and $(l+1)$. At the read side, the five data tracks $[r_{k,l}, r_{k,l+1}, r_{k,l+2}, r_{k,l+3}, r_{k,l+4}]$ are detected by an array of five read heads simultaneously (or using one single read head to detect these tracks one by one with the help of buffer memory).

In the RBP scheme,[5] we analyzed the signal amplitude of the kth data bit on the lth track (i.e., $c_{k,l}$) for different 3-by-3 data patterns, i.e., 3 bits from the upper track $[c_{k-1,l-1}, c_{k,l-1}, c_{k+1,l-1}]$, 3 bits from the lth center track $[c_{k-1,l}, c_{k,l}, c_{k+1,l}]$, and 3 bits from the lower track $[c_{k-1,l+1}, c_{k,l+1}, c_{k+1,l+1}]$, in the BPMR channel without noise. Then, we defined the data pattern that causes the readback amplitude of the detected bit to be an opposite polarity of the signal amplitude of the isolated bit, $c_{k,l}$, as a *destructive* data pattern.[5] By analyzing all destructive data patterns, we found that most of them are occurred when the kth bit of the adjacent tracks differs from that of the center track, i.e., $[c_{k,l-1}, c_{k,l}, c_{k,l+1}] = [1\ -1\ 1]$ or $[-1\ 1\ -1]$. Hence, we use this result to design the CITI code to avoid such destructive data patterns to be written onto a medium.

Here, we propose the rate-4/5 CITI coding scheme (will be explained later) for BPMR. The encoding and decoding processes are performed based on the look-up table, which can be constructed as follows. Define a vector $\mathbf{c}_{k,l}^N \equiv [c_{k,l}, c_{k,l+1}, \ldots, c_{k,l+N-1}]$ as a collection of the kth data bits from the N adjacent tracks starting with the lth track. Specifically, the CITI code maps the input data $\mathbf{a}_{k,l}^4$ to the recorded data $\mathbf{c}_{k,l}^5$ before recording it onto a medium.

Because $\mathbf{c}_{k,l}^5$ contains 5 bits, there are $2^5 = 32$ possible codewords in total. However, since the data pattern $\mathbf{c}_{k,j}^3 = [c_{k,j}, c_{k,j+1}, c_{k,j+2}]$, where $j \in \{l, l+1, l+2\}$, that causes the DITI is either $[1\ -1\ 1]$ or $[-1\ 1\ -1]$, the codeword that contains these data patterns must be discarded. In this case, we found 16 prohibited codewords. Thus, only 16 (good) codewords, $\tilde{\mathbf{c}}_l^5 \equiv [\tilde{c}_l, \tilde{c}_{l+1}, \tilde{c}_{l+2}, \tilde{c}_{l+3}, \tilde{c}_{l+4}]$, can be utilized to construct the CITI code, as shown in Table I. With 16 codewords, only 4 bits ($2^4 = 16$) are needed for the input of the CITI encoder, i.e., $\mathbf{a}_{k,l}^4$. Finally, we can assign a codeword $\tilde{\mathbf{c}}_l^5$ for each $\mathbf{a}_{k,l}^4$ so as to generate the look-up table for the CITI code, as given in Table I. Note that the recorded data $\mathbf{c}_{k,l}^5$ is the codeword that corresponds to the input data $\mathbf{a}_{k,l}^4$.

For decoding process, the estimated 5-track recorded sequence $\{\hat{c}_{k,l}\}$ is decoded by a CITI decoder, which uses the same look-up table in Table I, to determine the estimated 4-track input data sequence $\{\hat{a}_{k,l}\}$. Because of the noise, the decoding process might not be able to perform correctly for some data patterns $\hat{\mathbf{c}}_{k,l}^5 = [\hat{c}_{k,l}, \hat{c}_{k,l+1}, \hat{c}_{k,l+2}, \hat{c}_{k,l+3}, \hat{c}_{k,l+4}]$ that are not in Table I, i.e., $\hat{\mathbf{c}}_{k,l}^5 \neq \tilde{\mathbf{c}}_l^5$. To solve this problem, we propose to apply the Euclidean distance[8] concept in the CITI decoder to measure the resemblance between $\hat{\mathbf{c}}_{k,l}^5$ and $\tilde{\mathbf{c}}_l^5$. Specifically, for each codeword $\tilde{\mathbf{c}}_l^5$, the CITI decoder computes the Euclidean distance of $\hat{\mathbf{c}}_{k,l}^5$ according to $d(\hat{\mathbf{c}}_{k,l}^5, \tilde{\mathbf{c}}_l^5) = \sqrt{\sum_{i=0}^{4} (\hat{c}_{k,l+i} - \tilde{c}_{l+i})^2}$. Then, the estimated

TABLE I. A look-up table for the CITI code.

4-Bit input data, $\mathbf{a}_{k,l}^4$				5-Bit codeword, $\tilde{\mathbf{c}}_l^5$				
$a_{k,l}$	$a_{k,l+1}$	$a_{k,l+2}$	$a_{k,l+3}$	$\tilde{c}_l$	$\tilde{c}_{l+1}$	$\tilde{c}_{l+2}$	$\tilde{c}_{l+3}$	$\tilde{c}_{l+4}$
−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	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	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

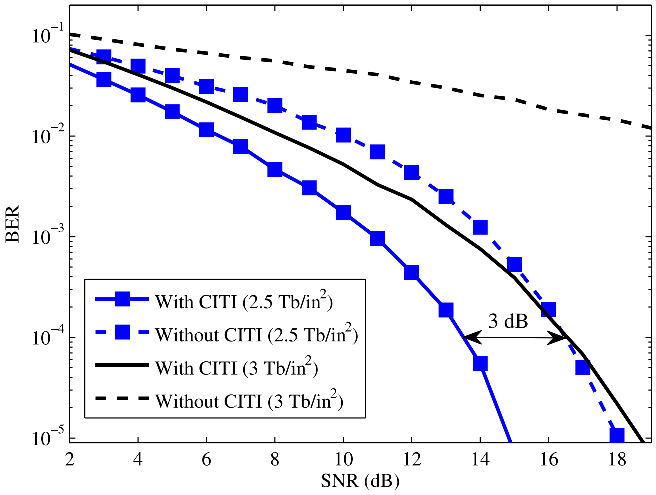

FIG. 2. BER performance at different areal densities without position jitter (i.e., $\sigma_j/T_x = 0\%$).

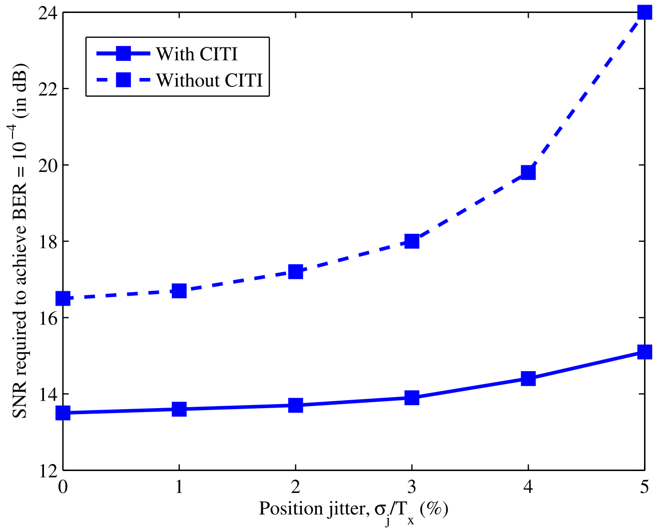

FIG. 3. Performance comparison for various position jitter amounts at 2.5 Tb/in.^{2}

input data $\hat{\mathbf{a}}_{k,l}^4 = [\hat{a}_{k,l}, \hat{a}_{k,l+1}, \hat{a}_{k,l+2}, \hat{a}_{k,l+3}]$ corresponding to the codeword $\tilde{\mathbf{c}}_l^5$ that yields the minimum $d(\hat{\mathbf{c}}_{k,l}^5, \tilde{\mathbf{c}}_l^5)$ will be chosen as the output of the CITI decoder.

In addition, the reason why the code rate of 4/5 is chosen can be explained as follows. First, we look at the number of data tracks needed for an N-bit codeword. Then, for each N, we ignore the total number of prohibited patterns so that the total number of good codewords, N_C, is obtained. Given N_C, the number of bits for the encoder input, M, can be computed from $M = \lfloor \log_2(N_C) \rfloor$, where $\lfloor v \rfloor$ is the greatest integer less than or equal to v. Finally, the code rate, R, of the CITI code can be calculated from $R = M/N$. Here, we consider $N = \{3, 4, 5, 6, 7\}$, whose code rate is $\{0.67, 0.75, 0.8, 0.67, 0.71\}$, respectively. Therefore, the rate-4/5 CITI code (i.e., $N = 5$) is preferred because of high code rate.

IV. SIMULATION RESULTS

We make a comparison between (1) the system with CITI coding in Fig. 1, where the two outer tracks $(l-1)$ and $(l+5)$ contain random data (denoted as "With CITI") and (2) the conventional system where an input sequence a_k is written onto a single track with random data on adjacent tracks (denoted as "Without CITI"). The signal-to-noise ratio (SNR) is defined as $10\log_{10}(1/R\sigma^2)$ in dB. 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[1,6] 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.[6]

Fig. 2 compares the BER performance of the system with and without CITI codes at the AD of 2.5 Tb/in.^{2} ($T_x = T_z = 16$ nm) and 3 Tb/in.^{2} ($T_x = T_z = 14.5$ nm) without position jitter, i.e., $\sigma_j/T_x = 0\%$. Clearly, the system with CITI coding outperforms that without CITI coding, especially at high ADs. Specifically, at BER $= 10^{-4}$, the proposed scheme can provide about 3 dB gain at 2.5 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. 3. It is apparent that the system with CITI coding is superior to that without CITI coding, especially when the position jitter is large.

V. CONCLUSION

In high-density BPMR, the ISI and ITI can be considered as a major cause of performance degradation. This paper proposes the rate-4/5 CITI coding scheme to mitigate the ITI. The key idea is to prevent the 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 CITI coding can provide a large performance gain if compared to that without CITI coding, especially when the areal density is high and/or the position jitter is large.

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