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A Rate-8/9 2-D Modulation Code for Bit-Patterned Media Recording

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The 2-D interference consisting of intersymbol and intertrack interferences is a major impairment in bit-patterned media recording (BPMR), especially at high-areal density (AD). One solution to mitigate the effect of 2-D interference is to apply a 2-D coding scheme on an input data sequence before recording so as to avoid some data patterns that easily cause an error at the data detection process. Nonetheless, this method usually requires many redundant bits, thus lowering a code rate. This paper proposes a rate-8/9 modulation code for a multitrack multihead BPMR system to eliminate the data patterns that lead to severe 2-D interference. Simulation 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. Specifically, for the system without position jitter at bit-error rate of 10^{-5}, the proposed system can provide 1.8 dB gain over the system without coding at the AD of 2.5 Tb/in^2.

***Index Terms*—2-D interference, bit-patterned media recording (BPMR), modulation code, position jitter.**

I. Introduction

BIT-PATTERNED media recording (BPMR) is one of the promising candidates for ultrahigh density storage devices whose areal density (AD) is beyond 1 Tb/in^2 [1]–[3]. In BPMR, each data bit is recorded on a single domain magnetic island surrounded by nonmagnetic material. To achieve high AD, the spacing between data bit islands in both the along- and across-track directions must be decreased, thus leading to the increase of 2-D interference. Practically, the 2-D interference consisting of intersymbol interference (ISI) and intertrack interference (ITI) can result in performance degradation if precautions are not taken.

In general, the effect of 2-D interference experienced in the detected bit can be either constructive or destructive, depending not only on the readback waveform of the detected bit but also on its surrounding bits [4]. Note that, this paper considers only the readback waveform without overshoot as shown in Fig. 1(b) [1], which can be obtained from the channel model shown in Fig. 2 (will be explained later). Specifically, given the signal amplitude of an isolated bit (or one single bit), the constructive/destructive interference will amplify/decrease its signal amplitude. Therefore, when the readback signal of the detected bit faces with the destructive interference, it could easily yield an error at the data recovery process.

Practically, there exist many 2-D coding schemes proposed in [4]–[9], which can prevent some data patterns that cause severe 2-D interference to be recorded onto a magnetic medium. For instance, Kurihara *et al.* [5] proposed a constructive ITI-coded partial-response (PR) maximum-likelihood system based on a two-track model for perpendicular magnetic recording. Specifically, this code was designed based on an equalized level such that the opposite polar level can never occur simultaneously after class-I PR equalization. Groenland and Abelmann [6] introduced a rate-7/9 2-D coding scheme to avoid the 2-D interference by placing the redundant bits in the fixed positions at every 3-by-3 data array. However,

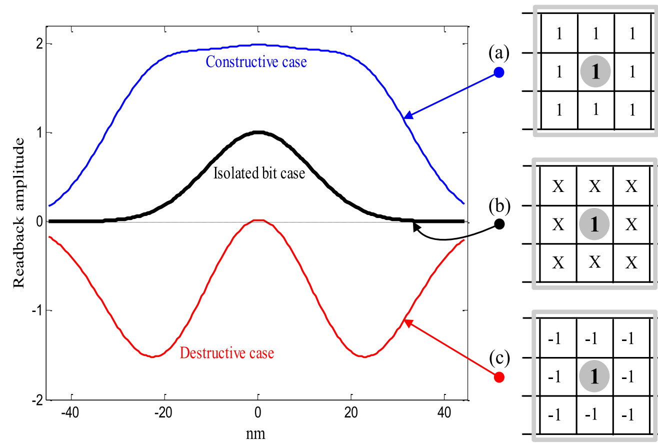

Fig. 1. Examples of the readback signal of (a) the constructive interference case when the bit 1 is surrounded by all 1s, (b) the isolated bit case, where X denotes no recorded bit, and (c) the destructive interference case when the bit 1 is surrounded by all -1s. All readback signals are generated based on the channel model in Fig. 2 without noise at 2.5 Tb/in^2.

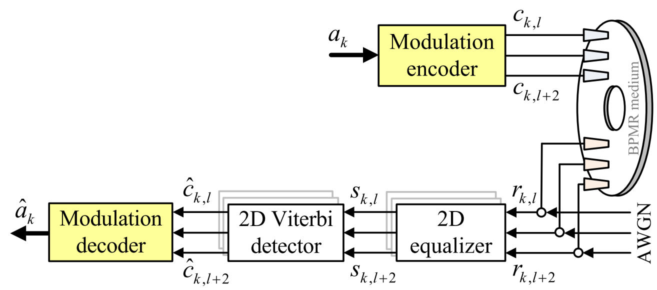

Fig. 2. BPMR channel model with the proposed coding scheme.

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this code had a drawback that the redundant bits had no error correction capability. Hence, Shao *et al*. [4] presented a rate-5/6 2-D code, which had lower redundancy and yielded a better performance than the code in [6]. Furthermore, a rate-4/6 modulation code was also proposed to eliminate the fatal 2-D ISI patterns in holographic data storage [7].

It should be pointed out that all of the above-mentioned coding schemes require many redundant bits, thus lowering a code rate. Therefore, another 2-D coding scheme was introduced [8], [9], which can efficiently alleviate the 2-D interference at the expense of high complexity and using large buffer memory. To improve its performance, we propose a rate-8/9 modulation code in this paper to combat the 2-D interference in a BPMR system. Specifically, every eight user bits will be mapped to a 9-bit codeword in the form of a 3-by-3 data array, based on a lookup table designed to avoid the data patterns that easily cause the destructive interference. This coding scheme assures that the BPMR readback signal will not be corrupted by the severe destructive interference, thus facilitating the data detection process.

The rest of this paper is organized as follows. Section II explains the BPMR channel model, whereas Section III briefly describes the proposed modulation code. Simulation results are given in Section IV. Finally, Section V concludes this paper.

II. BPMR Channel Model

Consider a multitrack multihead BPMR system [1], [3] with the proposed coding scheme in Fig. 2. An independent identically distributed binary input sequence $a_k \in \{\pm 1\}$ with bit period T_x is encoded by the proposed modulation encoder to obtain the three data tracks $\{c_{k,l},\ c_{k,l+1},\ c_{k,l+2}\}$, where $c_{k,i} \in \{\pm 1\}$ and $i \in \{l,\ l+1,\ l+2\}$, before recording them onto a medium. The readback signal from the kth data bit on the lth track can be written as

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

where $c_{k,l}$'s are the recorded bits, $\otimes$ is a 2-D convolution operator, $h_{m,n}$'s are the 2-D channel response coefficients [1], [2], m and n are the time indices of the bit island in the along- and across-track directions, respectively, and $w_{k,l}$ is an additive white Gaussian noise with zero mean and variance σ^2.

Practically, $h_{m,n}$'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 according to

$$h_{m,n} = P\,(mT_x, nT_z) \quad (2)$$

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

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

where $A = 1$ is supposed to be the peak amplitude of the pulse response, $b = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian pulse [1], PW_{50} is the width of the pulse response at half its maximum, Δ_x is the along-track location fluctuation (or position jitter [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. In this paper, 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.

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

III. Proposed Modulation Code

To simplify our discussion, 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 three readback sequences $\{r_{k,l},\ r_{k,l+1},\ r_{k,l+2}\}$ are detected by an array of three read heads simultaneously (or using one single read head to detect these tracks one by one with the help of buffer memory).

As studied in [8] and [9], the severity of 2-D interference mainly depends on the readback waveform of the detected bit (i.e., 1 or -1) and its surrounding bits, as shown in Fig. 1. For example, suppose we look at the readback signal for the isolated bit case in Fig. 1(b), where only one single bit (i.e., 1) is recorded on a medium and X denotes no recorded bit. It is clear that when the constructive/destructive interference occurs, the signal amplitude of the detected bit will be larger/smaller than that of the isolated bit case, as shown in Fig. 1(a) and (c). In practice, when the readback signal encounters the destructive interference, it could easily cause an error in the data recovery process, depending on how severe it is. For instance, Fig. 1(c) shows the readback signal that experiences the severe destructive interference, where in this case the detector might not be able to detect the bit 1 correctly.

To cope with the 2-D interference in the BPMR system, we propose a rate-8/9 modulation code to rearrange the user bits before recording them onto a magnetic medium. Generally, our proposed coding scheme is simple because its encoding and decoding processes are performed based on the lookup table, which can be described as follows.

A. Encoding Process

The proposed modulation encoder converts each of eight user bits $\mathbf{a}_k^8 \equiv [a_k, a_{k+1}, a_{k+2}, a_{k+3}, a_{k+4}, a_{k+5}, a_{k+6}, a_{k+7}]$ to the 9-bit recorded data $\mathbf{c}_k$ in the form of a 3-by-3 data array, which consists of three bits from the lth track $[c_{k,l}, c_{k+1,l}, c_{k+2,l}]$, three bits from the $(l+1)$th track $[c_{k,l+1}, c_{k+1,l+1}, c_{k+2,l+1}]$, and three bits from the $(l+2)$th

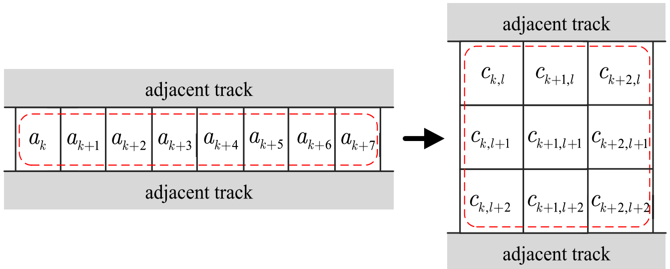

Fig. 3. Proposed encoding method, which maps the eight user bits to the 9-bit codeword in the form of a 3-by-3 data array.

track $[c_{k,l+2}, c_{k+1,l+2}, c_{k+2,l+2}]$, as shown in Fig. 3. With eight user bits, we need $2^8 = 256$ codewords for the proposed code. To achieve this, we introduce two coding schemes to tackle the 2-D interference for a multitrack multihead BPMR system.

For the first coding scheme, we exploit the result in [9] to design the 256 codewords, which can avoid the data patterns leading to severe 2-D interference to be written onto a medium. Specifically, we analyzed the signal amplitude of the kth data bit along the lth track (i.e., $a_{k,l}$) for all 3-by-3 data patterns ($2^9 = 512$ patterns), i.e., three bits from the upper track $[a_{k-1,l-1},\ a_{k,l-1},\ a_{k+1,l-1}]$, three bits from the lth center track $[a_{k-1,l},\ a_{k,l},\ a_{k+1,l}]$, and three bits from the lower track $[a_{k-1,l+1},\ a_{k,l+1},\ a_{k+1,l+1}]$, in the BPMR channel without noise. Accordingly, we defined the weight to determine the severity of 2-D interference, which was calculated based on the signal amplitude of each 3-by-3 data pattern and that of the isolated bit, as explained in [9]. It is evident that the 3-by-3 data pattern with the highest weight yields the least effect of 2-D interference [9]. Therefore, the top 256 3-by-3 data patterns with the highest weight will be used as the codewords in the first coding scheme.

Similarly, in [8], we defined the 3-by-3 data pattern that results in the signal amplitude of the center bit (e.g., $r_{l,k}$) to be an opposite polarity of the signal amplitude of the input bit $a_{l,k}$ as the destructive data pattern, which might cause the center bit to be detected in error. Thus, by analyzing all destructive data patterns in [8], 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., $[a_{k,l-1},\ a_{k,l},\ a_{k,l+1}]$ is either $[1\ -1\ 1]$ or $[-1\ 1\ -1]$. Therefore, we use this result to design the 256 codewords for the second coding scheme.

To do so, we define a column vector $\mathbf{c}_{k,l}^3 \equiv [c_{k,l}, c_{k,l+1}, c_{k,l+2}]^T$ as a collection of the kth recorded bits from the lth, $(l+1)$th, and $(1+2)$th tracks, where $[.]^T$ is the transpose operator. Because $\mathbf{c}_{k,l}^3$ contains three bits, there are $2^3 = 8$ patterns in total. However, by discarding two destructive patterns, i.e., $\mathbf{c}_{k,l}^3 = [1\ -1\ 1]$ or $[-1\ 1\ -1]$, we obtain six patterns of $\mathbf{c}_{k,l}^3$ that can be employed to construct the codewords. Since the three vectors $\{\mathbf{c}_{k,l}^3,\ \mathbf{c}_{k+1,l}^3$, and $\mathbf{c}_{k+2,l}^3\}$ will be concatenated into a codeword $\tilde{\mathbf{c}}_k$, we then obtain $6^3 = 216$ possible codewords. To get the 256 codewords for the second coding scheme, we choose the first 40 3-by-3 data patterns in [9] with the highest weight that are different from these 216 codewords.

Finally, we can assign a codeword $\tilde{\mathbf{c}}_k$ for each $\mathbf{a}_k^8$ so as to generate the lookup table for each proposed coding scheme. All these codewords guarantee that no data patterns resulting in the severe 2-D interference will be recorded onto a medium. It should be noted that the recorded data $\mathbf{c}_k$ is the codeword $\tilde{\mathbf{c}}_k$ that corresponds to the input data $\mathbf{a}_k^8$.

B. Decoding Process

After the 2-D Viterbi detection, the estimated three-track recorded sequence $\{\hat{c}_{k,l}\}$ will be decoded by a modulation decoder, which uses the same lookup table to determine the estimated input data sequence $\{\hat{a}_k\}$. Because of the noise, the decoding process might not perform reliably for some data patterns $\hat{\mathbf{c}}_k$ that are inconsistent with the 256 codewords, i.e., $\hat{\mathbf{c}}_k \neq \tilde{\mathbf{c}}_k$. To solve this problem, we apply the Euclidean distance concept [10] in the decoder to measure the resemblance between $\hat{\mathbf{c}}_k$ and $\tilde{\mathbf{c}}_k$. Specifically, for each codeword $\tilde{\mathbf{c}}_k$, the proposed decoder calculates the Euclidean distance of the received data pattern $\hat{\mathbf{c}}_k$ according to

$$d\left(\hat{\mathbf{c}}_k, \tilde{\mathbf{c}}_k\right) = \sqrt{\sum\nolimits_{m=0}^{2} \sum\nolimits_{n=0}^{2} \left(\hat{c}_{k+m,l+n} - \tilde{c}_{k+m,l+n}\right)^2}. \quad (4)$$

Hence, the estimated input data vector $\hat{\mathbf{a}}_k \equiv [\hat{a}_k, \hat{a}_{k+1}, \hat{a}_{k+2}, \hat{a}_{k+3}, \hat{a}_{k+4}, \hat{a}_{k+5}, \hat{a}_{k+6}, \hat{a}_{k+7}]$ corresponding to the codeword $\tilde{\mathbf{c}}_k$ that yields the minimum $d(\hat{\mathbf{c}}_k, \tilde{\mathbf{c}}_k)$ in (4) will be the output of the decoder.

IV. Simulation Results

In this paper, we focus on the BPMR system with a soft underlayer [1], [2]. Then, we consider only the 2-D Gaussian pulse response with the along-track PW_{50} of 19.4 nm and the across-track PW_{50} of 24.8 nm, similar to [2]. Specifically, this 2-D pulse response is obtained for a square magnetic island with a length of 11 nm and a thickness of 10 nm, using a magnetoresistive (MR) read head with an element thickness of 4 nm, an element width of 15 nm, a gap distance of 16 nm, and a fly height of 10 nm. Additionally, we consider the BPMR system at the AD of 2.5 Tb/in^2, where the bit period T_x, and the track pitch T_z are 16 nm, and the bit aspect ratio is assumed to be one. We also investigate the proposed coding schemes in the BPMR system at 3 Tb/in^2 by reducing T_x and T_z to 14.5 nm, where the dimensions of the MR head and the square island medium are fixed.

Here, we evaluate the performance of the proposed coding schemes in the BPMR system shown in Fig. 1, where the two outer tracks $(l-1)$ and $(l+3)$ contain random data. For the conventional system (no coding), an input sequence a_k is written onto a single track with random data on adjacent tracks, and the 2-D equalizer and the 2-D Viterbi detector are used (denoted as conventional). The signal-to-noise ratio (SNR) is defined as

$$\text{SNR} = 10\log_{10}\left(\frac{1}{R\sigma^2}\right) \quad (5)$$

in decibel, where R is a code rate. The 2-D 3-by-3 symmetric target and its corresponding 2-D 3-by-7 equalizer are designed based on a minimum mean-squared error approach [1], [3]

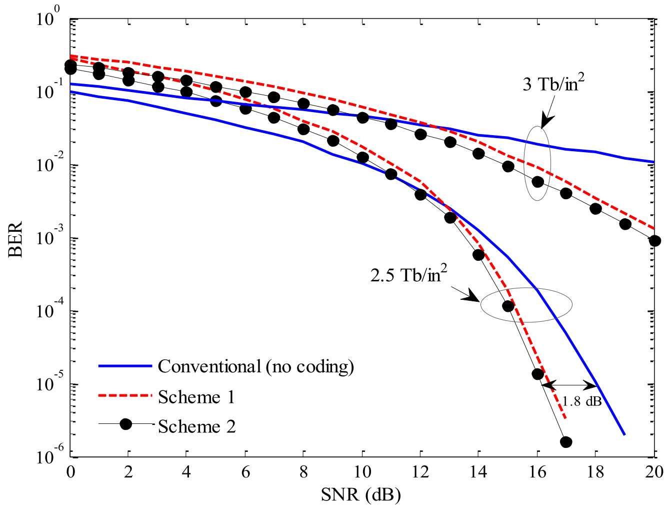

Fig. 4. BER performance of different systems without position jitter ($\sigma_j/T_x = 0\%$) at 2.5 and 3 Tb/in^2.

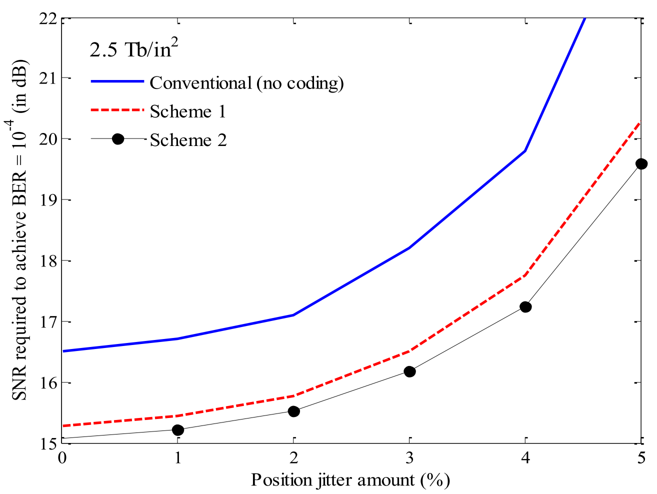

Fig. 5. Performance comparison at different position jitter amounts with AD = 2.5 Tb/in^2.

at the SNR required to achieve the bit-error rate (BER) of 10^{-4}. Notice that the 2-D Viterbi detector for this 3-by-3 symmetric target uses the trellis having 36 states with six parallel branches between any two connected states [1], [3]. Each BER point is computed using as many 4096-bit data sectors as needed to collect 500 erroneous bits.

Fig. 4 compares the BER performance of different systems at the ADs 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 second coding scheme performs slightly better than the first coding scheme, and both are superior to the conventional system, especially at high AD. Specifically, the second coding scheme performs the best and yields about 1.8 dB gain at BER $= 10^{-5}$ over the conventional system at AD of 2.5 Tb/in^2.

We also compare the performance of different systems at 2.5 Tb/in^2 by plotting the SNR required to achieve BER $= 10^{-4}$ as a function of position jitter amounts in Fig. 5. Again, the system with our coding schemes performs better than the conventional system, especially when the position jitter is large. Therefore, it can be implied that the proposed coding schemes are worth employing in the BPMR system.

V. Conclusion

At high AD, the 2-D interference consisting of ISI and ITI are very severe in the BPMR channel and can be considered a major cause of performance degradation. This paper focuses on how to subside the effect of 2-D interference and proposes the rate-8/9 modulation code. Specifically, each of eight user bits is converted into a 9-bit codeword in the form of a 3-by-3 data array, based on a lookup table. The key idea is to prevent the data patterns that easily cause an error at the data recovery process to be recorded onto a magnetic medium. Simulation results show that the system with our coding schemes performs better than that without coding, especially when an AD is high and/or the position jitter is large.

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