A Performance Improvement of a Rate-5/6 2D Modulation Code in Bit-Patterned Media Recording Systems

Kanoklekha Buahing[1], Wiparat Busyatras[1], Chanon Warisarn[1], Santi Koonkarnkhai[2], and Piya Kovintavewat[2]
[1]College of Advanced Manufacturing Innovation, KMITL, Bangkok–10520, Thailand
[2]Data Storage Technology Research Center, NPRU, Nakhon Pathom–73000, Thailand
E-mail: s8609013@kmitl.ac.th, s5690155@kmitl.ac.th, chanon.wa@kmitl.ac.th, and piya@npru.ac.th

Abstract: A reduction in a track width in magnetic recording systems results in a delightful increase in areal density (AD), but also in an unpleasant appearance of inter-track interference (ITI). One way the effect of severe ITI may be mitigated is through the use of coding schemes. In this paper, we improve the performance of a rate 5/6 two-dimension (2D) modulation code in bit-patterned media recording (BPMR) systems, and redesign code that efficiently eliminate ITI. Simulation results indicate that the proposed coding scheme is better than the conventional 2D modulation code, especially at high AD.

Keywords: Bit-pattern media recording, 2D interference, 2D Modulation code.

1. Introduction

Currently, conventional perpendicular magnetic recording (PMR) gets closer to near 1 terabits per square inch (Tb/in^2) recording density and further increase of the density may be challenging due to the well-known trilemma among media signal-to-noise ratio (SNR), writability, and thermal stability [1]. Bit-patterned media recording (BPMR) is one of the promising candidates for the next generation of hard disk drive (HDD) technology, which can cope these challenges. It is also expected to extend the areal density (AD) up to 4 Tb/in^2 [2]. However, when the track pitch and bit length in BPMR systems is reduced narrower to obtain the higher AD, the two-dimensional (2D) interference consisting of the inter-symbol interference (ISI) and inter-track interference (ITI) [3] will be also unsatisfactory increased. Moreover, the severe ITI can degrade the overall system performance significantly if a precaution is not considered to prevent this situation.

In previous work [4], we present the ITI-mitigating 5/6 modulation coding scheme to combat the destructive ITI (DITI), which converts an input data sequence into a 3-track recorded sequence 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 easing the data detection process. Normally, the Euclidean distance concept is applied in decoding process [4] to make sure that the received data can be decoded accordingly. However, we found that its performance can be improved using the new rearranged codeword scheme in the encoding process, which performs together with the data position identification of the codeword in the decoding process. These schemes not only easily perform but also lead to obtain a better performance. Thus, the bit-error rate (BER) performance can be significantly improved when the proposed coding scheme was adopted in the BPMR systems.

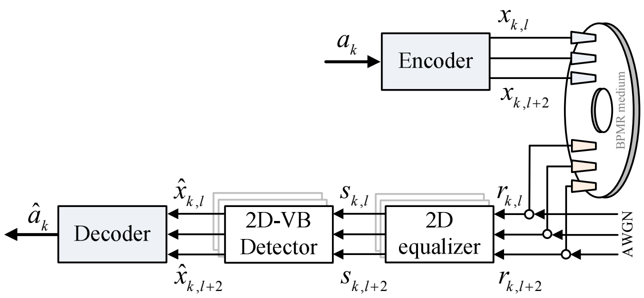


Fig. 1: Block diagram of BPMR systems with the proposed 2D modulation coding scheme.

2. BPMR Channel Model

A multi-track multi-head BPMR system with the proposed encoding/decoding scheme is considered in this paper as illustrated in Fig. 1. A binary input sequence $a_k \in \{\pm1\}$ with bit period T_x is encoded by the proposed modulation code to obtain the three data tracks $\{x_{k,l}, x_{k,l+1}, x_{k,l+2}\}$, where $x_{k,l} \in \{\pm1\}$, before recording them onto a medium. The readback signal from the k-th data bit along the l-th track can then be written as

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

where $x_{k,l}$'s are the recorded bits, $h_{m,n}$'s are the 2D channel response coefficients [3,4], m and n are the indices of the bit island in the along and across-track directions, $\otimes$ is the 2D convolution operator, and $n_{k,l}$'s are electronics noises modeled as an additive white Gaussian noise (AWGN) with zero-mean and variance σ^2.

In practice, $h_{m,n}$ can be obtained by sampling the isolated island pulse response at the integer multiples of the bit period T_x and the track pitch T_z according to [5,6]

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

where $P(x,z)$ is the 2D Gaussian pulse response given by

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

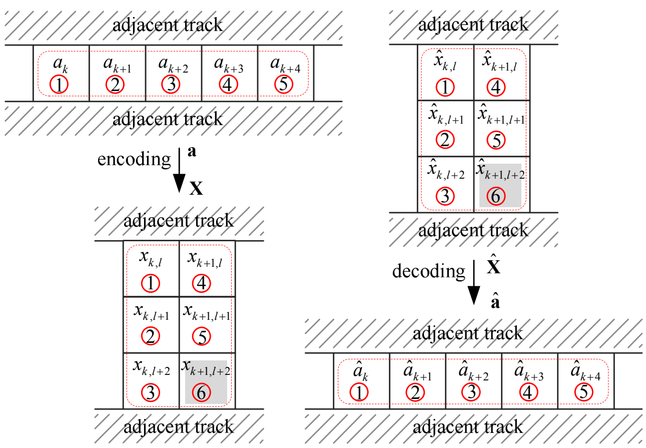
where, $\{m,n\} \in \{-L, ..., 0, ..., L\}$, $2L+1$ is the length of $P(x,z)$, L is an integer, z and x are the time indices in the across and the along-track directions, $A = 1$ is supposed to be the peak amplitude of $P(x,z)$, $c = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard deviation of the Gaussian pulse [7], PW_{50} is the pulse width at half of its peak value, Δ_x is the along-track location fluctuation (or position jitter [8]), 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_x 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 three readback sequences are equalized by the three 2D equalizers [9] to obtain the three equalized data sequences, $s_{k,l}$, and are then fed to each corresponding 2D Viterbi algorithm (VB) detectors to produce the three estimated recorded data sequences, $\hat{x}_{k,l}$, before passing them to the proposed encoder. Finally, we calculate the BER performance for evaluating the system performances.

3. Encoding and Decoding Scheme

We have analyzed the destructive data patterns [4], which found that most of them appear when the desired bit is surrounded with the opposite bits from the upper and lower tracks, i.e., $[x_{k,l-1}, x_{k,l}, x_{k,l+1}]$ is either $[1,-1, 1]^T$ or $[-1, 1,-1]^T$, where $[\cdot]^T$ is the transpose operator. Therefore, it is defined as the forbidden patterns, which are not always allowed to record on the medium.

A. Encoding Scheme

The conventional 5/6 modulation code [4] maps each of the 5 input bits $\mathbf{a} \equiv [a_k, a_{k+1}, a_{k+2}, a_{k+3}, a_{k+4}]$ to be a 6-bit codeword, $\mathbf{X}$, in the form of a 3-by-2 data matrix (or a codeword), which composes of 3 bits in the first column $[x_{k,l}, x_{k,l+1}, x_{k,l+2}]^T$, and 3 bits in the second column $[x_{k+1,l}, x_{k+1,l+1}, x_{k+1,l+2}]^T$, as shown in Fig. 2(a). However, it never been identified its position during the encoding process, which lead to hard for decoding. In this paper; therefore, the first 3-input bit will be added into the first column of codeword, while the remained 2-input data will be added into the second column of the codeword.



(a) (b)

Fig. 2: The proposed (a) encoding and (b) decoding schemes, which encode the 5 input bits to be a 6-bit codeword and decode the 6 estimated recorded bits to be the 5 estimated input bits, respectively.

However, the 6-th position will be defined as a redundant bit as seen in Fig. 2(a), which given to be the same data bit with the 5-th position. It is important to note that the first column must not be the forbidden patterns. Therefore, it still remains 8 patterns from 32 patterns that cannot encode by using our proposed scheme. Fortunately, we can employ both of conventional encoding and decoding to settle this problem. Table 1 and Fig. 3 show a look-up table and the list of all 32 codeword for the proposed coding scheme, respectively. Here, the vector **a** was assumed to be the 5-bit input data and matrix **X** are the codewords which obtained from encoding process as illustrated in Fig. 2 (a).

Table 1: A look-up table for the proposed coding scheme.

5-bit input data, **a**					**X** codeword
a_k	a_{k+1}	a_{k+2}	a_{k+3}	a_{k+4}	
-1	-1	-1	-1	-1	C_1
-1	-1	-1	-1	1	C_{11}
-1	-1	-1	1	-1	C_2
-1	-1	-1	1	1	C_{20}
-1	-1	1	-1	-1	C_9
-1	-1	1	-1	1	C_{14}
-1	-1	1	1	-1	C_{12}
-1	-1	1	1	1	C_6
-1	-1	-1	1	1	C_5
-1	-1	1	-1	-1	C_7
-1	-1	-1	-1	-1	C_3
-1	-1	1	1	1	C_{28}
-1	1	1	-1	-1	C_{18}
-1	1	1	-1	-1	C_{10}
-1	1	1	-1	1	C_{23}
-1	1	1	1	-1	C_{13}
-1	1	1	1	1	C_{31}
1	-1	-1	-1	-1	C_4
1	-1	-1	-1	1	C_{16}
1	-1	-1	1	-1	C_8
1	-1	-1	1	1	C_{24}
1	-1	-1	1	1	C_{21}
1	1	-1	1	1	C_{22}
1	1	-1	-1	-1	C_{27}
1	1	-1	-1	-1	C_{17}
1	1	-1	-1	1	C_{29}
1	1	-1	1	-1	C_{15}
1	1	-1	1	1	C_{26}
1	1	1	-1	-1	C_{19}
1	1	1	-1	1	C_{30}
1	1	1	1	-1	C_{25}
1	1	1	1	1	C_{32}

c_1		c_{11}		c_2		c_{20}	
-1	-1	-1	-1	-1	1	-1	1
-1	-1	-1	1	-1	-1	-1	1
-1	-1	-1	1	-1	-1	-1	1

c_9		c_{14}		c_{12}		c_6	
-1	-1	-1	-1	-1	1	-1	1
-1	-1	-1	1	-1	-1	-1	1
1	1	1	1	1	-1	1	-1

c_5		c_7		c_3		c_{18}	
-1	1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	1	1	1

c_{10}		c_{23}		c_{13}		c_{31}	
-1	-1	-1	-1	-1	1	-1	1
1	-1	1	1	1	-1	1	1
1	-1	1	1	1	-1	1	1

c_4		c_{16}		c_8		c_{24}	
1	-1	1	-1	1	1	1	1
-1	-1	-1	1	-1	-1	-1	1
-1	-1	-1	1	-1	-1	-1	1

c_{21}		c_{22}		c_{27}		c_{28}	
1	1	1	1	1	-1	-1	1
-1	1	1	1	1	-1	-1	1
-1	-1	-1	-1	-1	1	1	1

c_{17}		c_{29}		c_{15}		c_{26}	
1	-1	1	-1	1	1	1	1
1	-1	1	1	1	-1	1	1
-1	-1	-1	1	-1	-1	-1	1

c_{19}		c_{30}		c_{25}		c_{32}	
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. 3: A list of all 32 codewords for avoiding the severe ITI in bit-patterned media recording systems.

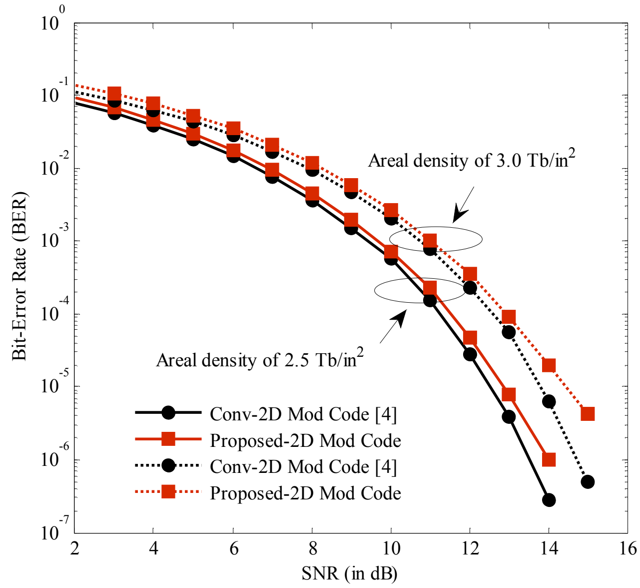


Fig. 4: BER performance comparison of the proposed coding scheme and conventional 2D modulation [4] at the ADs of 2.5 and 3.0 Tb/in^2.

B. Decoding Scheme

For the decoding process, the 6 estimated recorded bits, $\hat{\mathbf{X}}$, will be rearranged to be the 5 estimated input bits, $\hat{\mathbf{a}}$, as illustrated in Fig. 2(b). The first column is filled at the 1-st to the 3-rd position of the estimated input slot, while the remained 2 bits, i.e., the data at the 4-th and 5-th position are added at the 4-th and 5-th position, respectively. These encoding and decoding schemes not only easily perform but also yield a better performance.

4. Results and Discussion

We compare the BER performance between the proposed scheme and the conventional 2D modulation code [4], which denoted as "Proposed-2D Mod Code" and "Conv-2D Mod Code [4]", respectively. We consider the ADs of 2.5 and 3.0 Tb/in^2, which correspond with the track pitch and bit length of 16.0 nm and 14.5 nm, respectively [3,4]. In this paper, the AD is defined as [10]

$$\mathrm{AD} = \frac{10^6}{1550(T_x T_z)}, \tag{4}$$

and the SNR is defined as

$$\mathrm{SNR} = 10\log_{10}\left(1/\mathrm{R}\sigma^2\right), \tag{5}$$

where R is code rate, i.e., R = 0.833, "1" is assumed to be the peak amplitude of the readback signal. In Fig. 4, it is clear that the proposed coding scheme is slightly better than the conventional 2D modulation code for about 0.4 dB at BER = 10^{-5} and AD of 2.5 Tb/in^2 (T_x = T_z = 16 nm). However, we can gain more than 0.8 dB over the conventional one at BER = 10^{-5} when the AD is higher, e.g., at 3.0 Tb/in^2 (T_x = T_z = 14.5 nm). The reason may be, because the data position identification in the codeword can lead to obtain more accuracy in the decoding process.

5. Conclusion

This paper proposes the new encoding and decoding schemes to improve the performance of a rate 5/6 2D modulation code in BPMR systems. The codeword is carefully redesigned using the data position identification of codeword, which lead to easily perform in both of encoding and decoding processes. Moreover, the redundant bit can also help to prevent the severe ITI situation. The results indicate that the system performance can be significantly improved when the proposed coding scheme is adopted in the multi-track multi-head BPMR systems, especially when the AD is high.

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