A Simple Recorded-Bit Patterning Scheme for Bit-Patterned Media Recording

Autthasith Arrayangkool[1], Chanon Warisarn[1], Lin M. M. Myint[2], and Piya Kovintavewat[3]
[1]College of Data Storage Innovation, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand
[2]School of Information Technology, Shinawatra University, Pathum Thani 16120, Thailand
[3]Data Storage Technology Research Center, Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand
[1]s4690151@kmitl.ac.th, [1]kwchanon@kmitl.ac.th, [2]lin@siu.ac.th, [3]piya@npru.ac.th

***Abstract*—In bit-patterned magnetic recording (BPMR), inter-symbol interference (ISI) and inter-track interference (ITI) become a major impairment due to small bit and track pitches. One way to alleviate ISI and ITI is to encode the data sequence before recording. In general, two-dimensional (2D) coding scheme requires many redundant bits, thus lowering the code rate. This paper proposes a novel 2D coding scheme (referred to as a simple recorded-bit patterning (RBP) scheme) with high code rate to combat both ISI and ITI effects. Specifically, the data bits will first be patterned by finding the best data pattern based on a look-up table that can avoid severe ISI and ITI effects before recording. Simulation results indicate that the proposed scheme can provide a significant performance improvement if compared to the system without coding.**

Keywords—BPMR; position jitter noise; recorded-bit patterning (RBP); two-dimensional equalization

I. INTRODUCTION

To keep up with the rapidly growing demand for data storage, a recording density must be increased to an ultra-high level for future storage systems. Bit-patterned media recording (BPMR) is one of the promising candidates for the next generation of hard disk drive (HDD) technology, which is expected to achieve the areal density up to 4 terabits per square inch (Tb/in^2) [1]. Because of high recording densities, BPMR has very small gap between data bit islands in both the along-track and the across-track directions, thus causing two-dimensional (2D) interference consisting of inter-symbol interference (ISI) and inter-track interference (ITI) [2]-[4], which degrades the overall system performance significantly.

Generally, the 2D interference effect can be constructive and destructive, which is determined by the readback waveform of the detected bit and the value of its surrounding bits. In this paper, we consider the readback waveform without overshoot as shown in Fig. 1 [5]. Specifically, the signal amplitude of the detected bit (or the center bit) is boosted if all surrounding bits within a 3-by-3 data array have same polarity as the detected bit, which is referred to as the *best* case. On the other hand, the signal amplitude of the detected bit is dropped if all surrounding bits have opposite polarity, which is referred to as the *worst* case. Clearly, in the worst case, because the signal amplitude of the detected bit is poor, it can easily cause an error at the data recovery process.

To avoid the destructive interference, the constructive ITI code based on the equalized level of class-I partial response was proposed in [2]. Next, the authors in [3] presented a 2D coding scheme with a code rate of 7/9 to avoid the worst case, where the redundant bits were placed in fixed positions at every 3-by-3 data array. Nonetheless, the drawback of this scheme is that the redundant bits had no error correction ability. Therefore, another 2D coding scheme with a code rate of 5/6 was introduced in [4], which has lower redundancy and yields better performance than the 2D code in [3]. However, this paper proposes a simple RBP scheme with high code rate to avoid the destructive interference. In the RBP scheme, we split a data sequence into three tracks, and then rotate them to find the best pattern based on a look-up table before recording the resulting data bits onto a medium.

The paper is organized as follows. After describing a BPMR channel model in Section-II, Section-III explains how the proposed RBP scheme works. Simulation results are given in Section-IV. Finally, Section-V concludes this paper.

II. CHANNEL MODEL

Fig. 2 illustrates the BPMR channel model with the RBP scheme. A binary input sequence $a_k \in \{\pm 1\}$ with bit period T_x is split into three tracks, and then is sent to the RBP transmitter block. The readback signal from the k^{th} data bit on the l^{th} track can be expressed as [5]

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

where $x_{l,k}$'s are the recorded bits on the islands, $h_{m,n}$'s are the 2D channel response coefficients, n and m represent the indices of the bit islands in the along-track direction and the across-track direction, $\otimes$ is the 2D convolution operator, and $n_{l,k}$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ^2. For the BPMR system, the channel response coefficient $h_{m,n}$'s can be generated by sampling the isolated island's pulse response at integer multiples of the bit period T_x and the track pitch T_z, i.e.,

978-1-4799-0545-4/13/$31.00 ©2013 IEEE

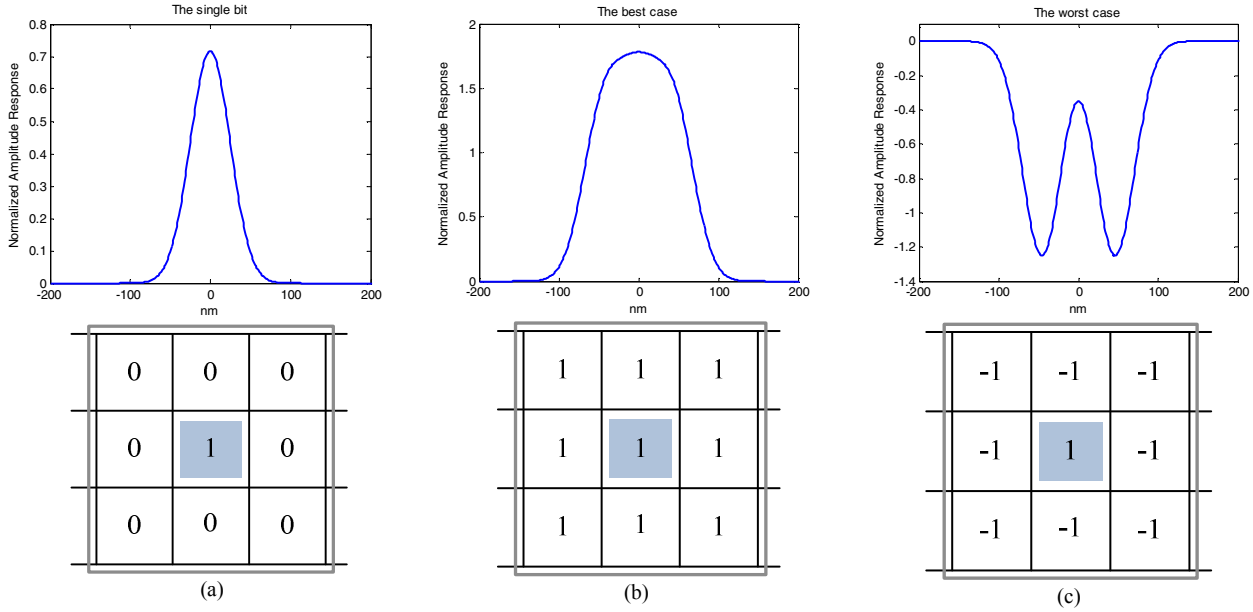

Fig. 1. The readback signal of (a) one single bit, (b) the best case when the '1' bit is surrounded by all '1' bits, and (c) the worst case when the '1' bit is surrounded by all '-1' bits. All of them are generated without any noises.

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

where $P(x, z)$ is the 2D Gaussian pulse response [5], and $2L+1$ is the 2D channel length. The 2D Gaussian pulse response for the BPMR system in this study is given by [5, 6]

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

where $A = 1$ is assumed to be the peak amplitude of the 2D pulse response, Δ_x is the along-track location fluctuation, Δ_z is the across-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, PW_{50} is the pulse width at half its maximum, $c = 1/2.3458$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian. In this paper, we assume that there is only the position jitter noise in the along-track direction (i.e., $\Delta_z = 0$), and the position jitter noise Δ_x is modeled as a truncated Gaussian probability distribution function with zero mean and variance σ_j^2, where σ_j is specified as percentage of the bit period T_x.

In this work, we assume that only two adjacent tracks (l–1) and (l+1) cause most of ITI, and consider the BPMR medium with two guard bands for the two outer tracks (l–2) and (l+2). Specifically, we assume that the three input data sequences $[x_{l-1,k}\ x_{l,k}\ x_{l+1,k}]$ are recorded on the three adjacent tracks (l–1), (l), and (l+1), respectively. These three data tracks will be 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 the buffer memory). Then, the readback data sequence $r_{l,k}$ is equalized by a 2D equalizer [6] to obtained the data sequences $s_{l,k}$, and is fed to the 2D Viterbi detector [5] to determine the most likely input sequence. Finally, the RBP receiver block is used to rearrange the data sequence with an aid of the redundant bits.

III. A PROPOSED RBP SCHEME

Because the severity of 2D interferences depends on both the readback waveform and the surrounding bits, we propose a simple RBP scheme by rearranging data bits to avoid some data patterns that easily cause an error at the data recovery process. To achieve this, we consider the channel model without noise and position jitter noise, where one single bit will produce a readback waveform without overshoot as depicted in Fig. 1(a).

We define a *window* of a 3-by-3 array that covers 9 bits, i.e., 3 bits from the upper track $[a_{l-1,k-1}\ a_{l-1,k}\ a_{l-1,k+1}]$, 3 bits from the center track $[a_{l,k-1}\ a_{l,k}\ a_{l,k+1}]$, and 3 bits from the lower track $[a_{l+1,k-1}\ a_{l+1,k}\ a_{l+1,k+1}]$, as demonstrated in Fig. 3. Using this window, we search for the data pattern $[a_{l-1,k-1}\ a_{l-1,k}\ a_{l-1,k+1}\ a_{l,k-1}\ a_{l,k}\ a_{l,k+1}\ a_{l+1,k-1}\ a_{l+1,k}\ a_{l+1,k+1}]$ that can easily cause an error at the detector. For simplicity, we define the data pattern that results in the readback amplitude of the center bit $\{r_{l,k}\}$ to be an opposite polarity of the signal amplitude of $\{a_{l,k}\}$ as a *destructive* data pattern. Table I shows all destructive data patterns that cause the center bit to be detected in error. In addition, the rest of all possible data patterns within the window will be considered as a *constructive* data pattern.

Therefore, this paper classifies the 2D interference into two cases, namely constructive and destructive interferences, as shown for example in Fig. 1(b) and Fig. 1(c), respectively. Specifically, when the '1' bit is surrounded by all '1' bits, it yields the constructive interference resulting in the relative

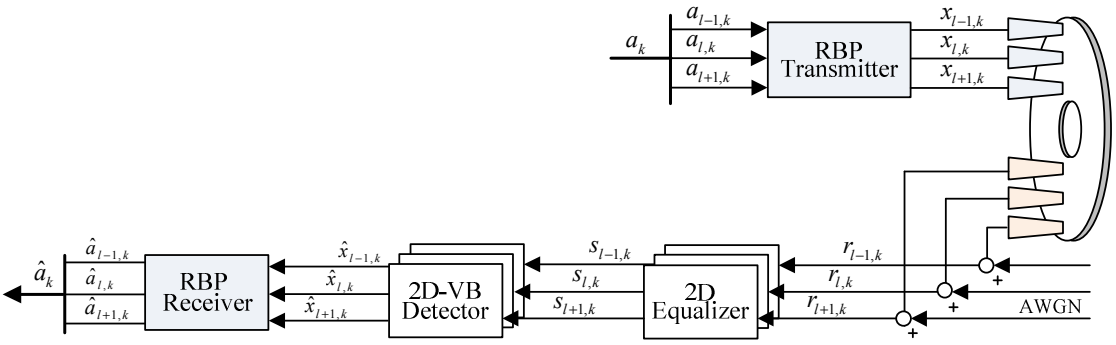

Fig. 2. Block diagram of bit-patterned media recording system.

TABLE I. DESTRUCTIVE DATA PATTERNS

Destructive Pattern Number	Upper Track			Center Track			Lower Track		
	$(k\text{-}1)^{th}$	k^{th}	$(k\text{+}1)^{th}$	$(k\text{-}1)^{th}$	k^{th}	$(k\text{+}1)^{th}$	$(k\text{-}1)^{th}$	k^{th}	$(k\text{+}1)^{th}$
1	1	1	1	1	-1	1	1	1	1
2	-1	1	1	1	-1	1	1	1	1
3	1	1	-1	1	-1	1	1	1	1
4	-1	1	-1	1	-1	1	1	1	1
5	1	1	1	-1	-1	1	1	1	1
6	1	1	1	1	-1	-1	1	1	1
7	1	1	1	1	-1	1	-1	1	1
8	-1	1	1	1	-1	1	-1	1	1
9	1	1	-1	1	-1	1	-1	1	1
10	-1	1	-1	1	-1	1	-1	1	1
11	-1	-1	1	-1	1	-1	1	-1	1
12	1	-1	-1	-1	1	-1	1	-1	1
13	-1	-1	-1	-1	1	-1	1	-1	1
14	1	-1	1	-1	1	-1	-1	-1	1
15	-1	-1	1	-1	1	-1	-1	-1	1
16	1	-1	-1	-1	1	-1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1	-1	1
18	1	1	1	1	-1	1	1	1	-1
19	-1	1	1	1	-1	1	1	1	-1
20	1	1	-1	1	-1	1	1	1	-1
21	-1	1	-1	1	-1	1	1	1	-1
22	1	1	1	1	-1	1	-1	1	-1
23	-1	1	1	1	-1	1	-1	1	-1
24	1	1	-1	1	-1	1	-1	1	-1
25	1	-1	1	-1	1	-1	1	-1	-1
26	-1	-1	1	-1	1	-1	1	-1	-1
27	1	-1	-1	-1	1	-1	1	-1	-1
28	-1	-1	-1	-1	1	-1	1	-1	-1
29	-1	-1	-1	-1	1	1	-1	-1	-1
30	-1	-1	-1	1	1	-1	-1	-1	-1
31	1	-1	1	-1	1	-1	-1	-1	-1
32	-1	-1	1	-1	1	-1	-1	-1	-1
33	1	-1	-1	-1	1	-1	-1	-1	-1
34	-1	-1	-1	-1	1	-1	-1	-1	-1

high amplitude of the readback signal at the center position. This will be referred to as the *best* case. On the other hand, the destructive interference is occurred when the '1' bit is surrounded by all '–1' bits, which significantly decreases the amplitude of the readback signal at the center position. This will also be referred to as the *worst* case because the center bit extracted from this readback signal can be easily detected in error.

The detail on how the proposed BRP scheme works can be explained as follow. Given the three data tracks, we move the

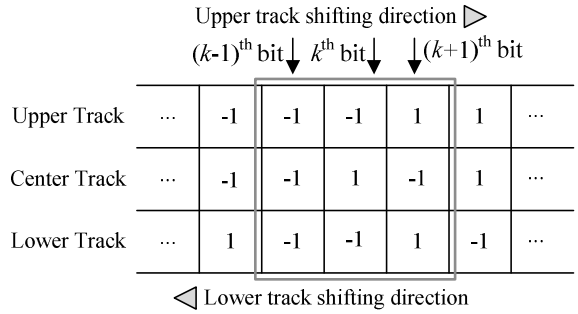

Fig. 3. The simple RBP scheme, where the center track is fixed and the upper and lower tracks are circularly shifted. The data bits in the window (a 3-by-3 square block) are considered.

3-by-3 window (centered at the center track as shown in Fig. 3) from the beginning to the end of the tracks, and count the total number of data patterns that corresponds to the one listed in Table I (i.e., destructive data pattern).

We circularly shift the upper track and the lower track to create all possible data patterns (i.e., the center track is fixed). Then, for each shifting time, we perform a similar procedure to count the total number of destructive data patterns. Finally, the number of shifting times (used in the upper and the lower tracks) that yields the lowest number of destructive data patterns will be added at the end of the data sequence (serving as the redundant bits). This number of shifting times will be employed to shift the data bits back to the original position at the RBP receiver block. For simplicity, we assume there is no error detected in these redundant bits in this study.

Although the proposed RBP scheme takes large processing time especially when the data track is long, it can be reduced by dividing the data track into many portions. In this work, we first split one 4032-bitdata sector $\{a_k\}$ into three data track, each with 1344 bits (i.e., a 3-by-1344 data array). Then, to reduce the processing time, we divide the 3-by-1344 data array into 21 portions with 3-by-64 data array each. With this splitting method, the code rate of this system can be calculated from $(3\times64)/(3\times64 + 2\log_2 q)$, where $q = 64$ is the maximum number of possible shifting times in each track. Hence, the code rate in this case is 0.9412.

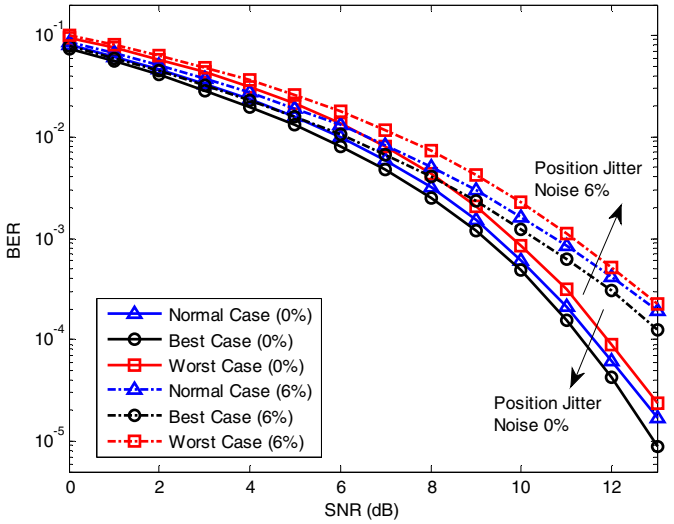

Fig. 4. BER performance of different schemes with 0% and 6% position jitter noise.

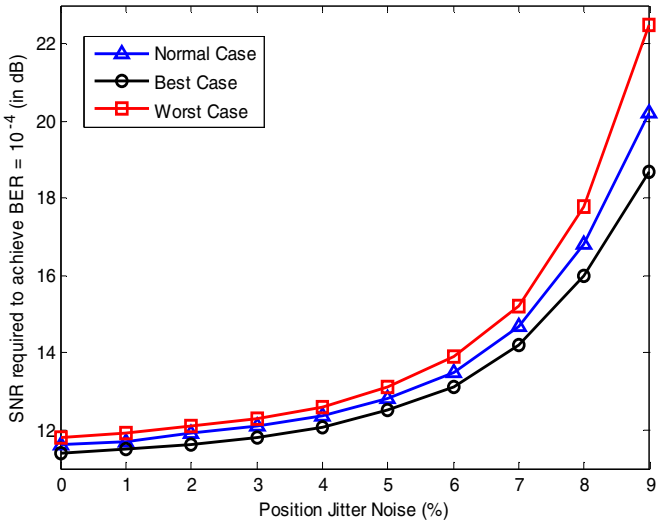

Fig. 5. Performance comparison of different schemes at different position jitter noise amounts.

IV. Simulation Results

We test the proposed RBP scheme in the BPMR system as shown in Fig. 2 with an areal density of 2 Tb/in^2, where the bit period and the track pitch are 18 nm, the along-track PW_{50} is 19.4 nm, and across-track PW_{50} is 24.8 nm as similar to [7]. A signal-to-noise ratio is defined as

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

in decibel (dB), where σ is a standard deviation of AWGN. The 2D 3-by-3 target and 2D 3-by-7 equalizer are designed based on a MMSE approach [5, 8] 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 4032 bits.

Fig. 4 shows the BER performance of different schemes for BPMR system with $\sigma_j = 0\%$ and $\sigma_j = 6\%$ position jitter noise. Note that the percentage inside the parenthesis in Fig. 4 indicates the percentage of the position jitter noise used to generate each curve. 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 noise. In addition, when the position jitter noise is increased from 0% to 6%, the Best Case still provides better performance than the others, and yields about 0.5 dB and 1 dB gain at BER = 10^{-4} over the Normal Case and the Worst Case, respectively. This is because the proposed RBP scheme 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 noise amounts in Fig. 5, 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, especially when the position jitter noise is severe (i.e., at 9% position jitter noise).

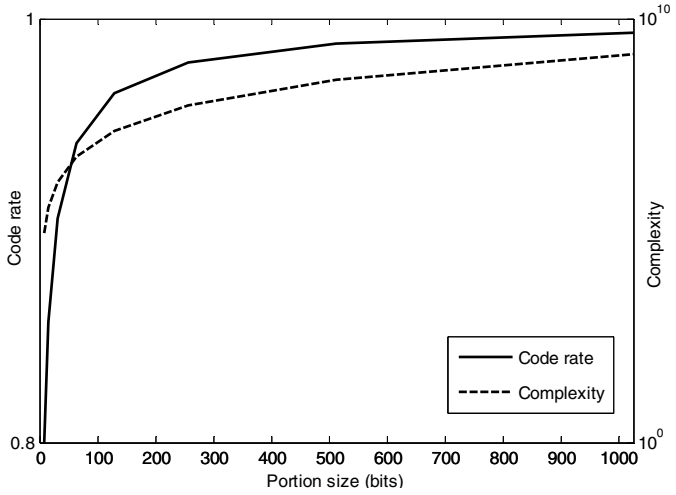

Fig. 6. The code rate and the complexity of the proposed RBP scheme as a function of portion sizes.

Furthermore, we analyze the code rate and the complexity of the proposed RBP scheme when varying the portion size used to divide the data track. In this paper, the complexity is defined as the total number of shifting times. Here, we consider the portion sizes of 8, 16, 32, 64, 128, 256, 512, and 1024 bits. It can be shown that the code rate can be calculated from

$$R = \frac{n_t n_b}{n_t n_b + 2\log_2(q)}, \tag{5}$$

where n_t is the number of data tracks and n_b is the portion size. Additionally, the complexity can be computed from

$$C = n_u \times n_l \times n_w \times n_p, \tag{6}$$

TABLE II. COMPLEXITY AND CODE RATE COMPARISON

Portion sizes	Complexity	Complexity, C	Code rate, R
		$L_t = 1344$	$L_t = 1344$
8	64 L_t	86016	0.8000
16	256 L_t	344064	0.8571
32	1024 L_t	1376256	0.9057
64	**4096 L_t**	**5505024**	**0.9412**
128	16384 L_t	22020096	0.9648
256	65536 L_t	88080384	0.9796
512	262144 L_t	352321536	0.9884
1024	1048576 L_t	1409286144	0.9935

where n_u and n_l are the maximum number of possible shifting times in the upper and the lower tracks, respectively, n_w is the number of shifting times for the 3-by-3 window, $n_p = L_t / n_b$ is the number of portions in each block, and L_t is the number of bits in each track. In general, n_u, n_l and n_w are equal to n_b. Therefore, the proposed RBP scheme has the complexity of $C = n_b^2 \times L_t$. Fig. 6 displays the code rate and the complexity as a function of the portion sizes. It is apparent that the complexity and the code rate increase as the portion size increases. Furthermore, Table II also shows the complexity and the code rate of the proposed RBP scheme in details.

V. CONCLUSION

This paper proposed the simple RBP scheme to mitigate the 2D interference effect that exists in BPMR system. The basic idea is to avoid the destructive data patterns (i.e., the data pattern that easily causes an error at data recovery process) before writing the pre-patterned data onto a medium. Simulation results show that the proposed RBP scheme can help improve the BPMR system performance, especially when the system faces with severe position jitter noises. Although the proposed RBP scheme provides good performance with high code rate, all advantages gained by the proposed RBP scheme need to be balanced against the increased processing time. Thus, more research work is required so as to develop an efficient RBP scheme that performs rapidly and requires a smaller number of the redundant bits.

ACKNOWLEDGMENT

This work was supported by College of Data Storage Innovation (D*STAR) and King Mongkut's Institute of Technology Ladkrabang Research Fund, Thailand. The author would like to thank Assoc. Prof. Pornchai Supnithi for helping and his valuable advice.

REFERENCES

[1] W. Chang and J. R. Cruz, "Inter-Track Interference Mitigation for Bit-Patterned Magnetic Recording," *IEEE Trans. Magn.*, vol. 46, no. 11, pp. 3899–3908, Nov. 2010.

[2] Y. Kurihara, Y. Takeda, Y. Takaishi, Y. Koizumi, H. Osawa, M.Z. Ahmed, and Y. Okamoto, "Constructive ITI-coded PRML system based on a two-track model for perpendicular magnetic recording," Journal of Magnetism and Magnetic Materials 320, pp. 3140-3143, Aug. 2008.

[3] J. P. J. Groenland and L. Abelmann, "Two dimentional Coding for Probe Recording on Magnetic Patterned Media," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2307–2309, Jun. 2007.

[4] X. Shao, L. Alink, J.P.J. Groenland, L. Abelmann, and C. H. Slump, "A Simple Two-Dimensional Coding Scheme for Bit Patterned Media," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 2559-2562, Oct. 2011.

[5] S. Nabavi, B. V. K. Vijaya Kumar, and J. A. Bain, Signal processing for bit-patterned media channel with inter-track interference, Ph.D. dissertation, Dept. Elect.Eng. Comp. Sci., Carnegie Mellon University, Pittsburgh, PA, 2008.

[6] S. Koonkarnkhai, N. Chirdchoo, and P. Kovintavewat, "Iterative Decoding for High-Density Bit-Patterned Media Recording," Procedia Engineering 32, pp.323-328, Nov. 2012.

[7] S. Nabavi *et al.*, "Application of Image Processing to Characterize Patterning Noise in Self-assembled Nano-masks for Bit-Patterned media," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 3523–3527, Oct. 2009.

[8] J. Moon and W. Zeng, "Equalization for maximum like-lihood detector," *IEEE Trans. Magn.*, vol. 31, no. 2, pp. 1083–1088, Mar. 1995.