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A Recorded-Bit Patterning Scheme with Accumulated Weight Decision for Bit-Patterned Media Recording

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SUMMARY To achieve high recording density in a bit-patterned media recording system, the spacing between data bit islands in both the along-track and the across-track directions must be decreased, thus leading to the increase of two-dimensional (2D) interference. One way to reduce the 2D interference is to apply a 2D coding scheme on a data sequence before recording; however, this method usually requires many redundant bits, thus lowering a code rate. Therefore, we propose a novel 2D coding scheme referred to as a recorded-bit patterning (RBP) scheme to mitigate the 2D interference, which requires no redundant bits at the expense of using more buffer memory. Specifically, an input data sequence is first split into three tracks in which will then be rotated to find the best 3-track data pattern based on a look-up table before recording, such that the shifted data tracks yield the least effect of 2D interference in the readback signal. Numerical results indicate that the proposed RBP scheme provides a significant performance improvement if compared to a conventional system (without 2D coding), especially when the recording density is high and/or the position jitter noise is large.

key words: *bit-patterned media recording, position jitter noise, recording-bit patterning, two-dimensional equalization*

1. Introduction

To meet with an enormous demand for digital data storage, the recording density of future storage devices must be continuously increased. Recently, a hard disk drive (HDD) employs the perpendicular magnetic recording (PMR) technology. Because the continuous medium used in current HDDs has physical and engineering limitations due to the superparamagnetic limit [1], it prevents us from increasing the storage capacity beyond 1 terabits per square inch (Tb/in^2). Thus, more unconventional technological solutions become crucial. Bit-patterned media recording (BPMR) is one of the promising candidates for the next generation's HDD technology that can achieve an areal density up to 4 Tb/in^2 [2].

In general, to achieve high recording density in BPMR, the spacing between data bit islands in both the along-track and the across-track directions must be reduced, thus leading to the increase of two-dimensional (2D) interference. It should be noted that the 2D interference consists of inter-symbol interference (ISI) and inter-track interference (ITI) [3]–[5], which can significantly deteriorate the system performance.

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Practically, the effect of 2D interference experienced in the detected bit (i.e., +1 or −1) can be either constructive or destructive, depending on the readback waveform of the detected bit and its surrounding bits [5]. In this paper, we consider only the readback waveform without overshoot as shown in Fig. 1 [6], which can be obtained from the channel model shown in Fig. 2 (will be explained later). Specifically, given a 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 cause an error at the data recovery process.

Many works have recently been proposed to cope with the 2D interference. For instance, the authors in [3] proposed a constructive ITI-coded partial-response (PR) maximum-likelihood system based on a two-track model for PMR systems. Specifically, the constructive ITI codes were designed based on the equalized level such that the opposite polar level can never occur simultaneously after class-I PR equalization. In addition, the 2D coding scheme with a code rate of 7/9 was specially designed in [4] to avoid the destructive interference case, where the redundant bits were placed in fixed positions at every 3-by-3 data array. Nonetheless, this coding scheme had a drawback that the redundant bits had no error correction capability. Thus, Shao et al. [5] introduced another 2D coding scheme with a code rate of 5/6, which had lower redundancy and yielded better performance than the code presented in [4].

However, this paper proposes a novel recorded-bit patterning (RBP) scheme without redundant bit (i.e., a code rate of 1) to combat the 2D interference, at the expense of using more buffer memory. To achieve this, a data sequence is first split into three tracks in which will then be rotated to find the *best* data pattern based on the look-up table. Here, the best data pattern is defined as the data pattern with the *maximum* accumulated weight, which causes the least destructive effect of 2D interference in the readback signal.

The rest of this paper is organized as follows. Section 2 describes a BPMR channel model, and Sect. 3 explains the proposed RBP scheme. Simulation results are given in Sect. 4. Finally, Sect. 5 concludes this paper.

2. Channel Model

Figure 2 illustrates the BPMR channel model with the RBP

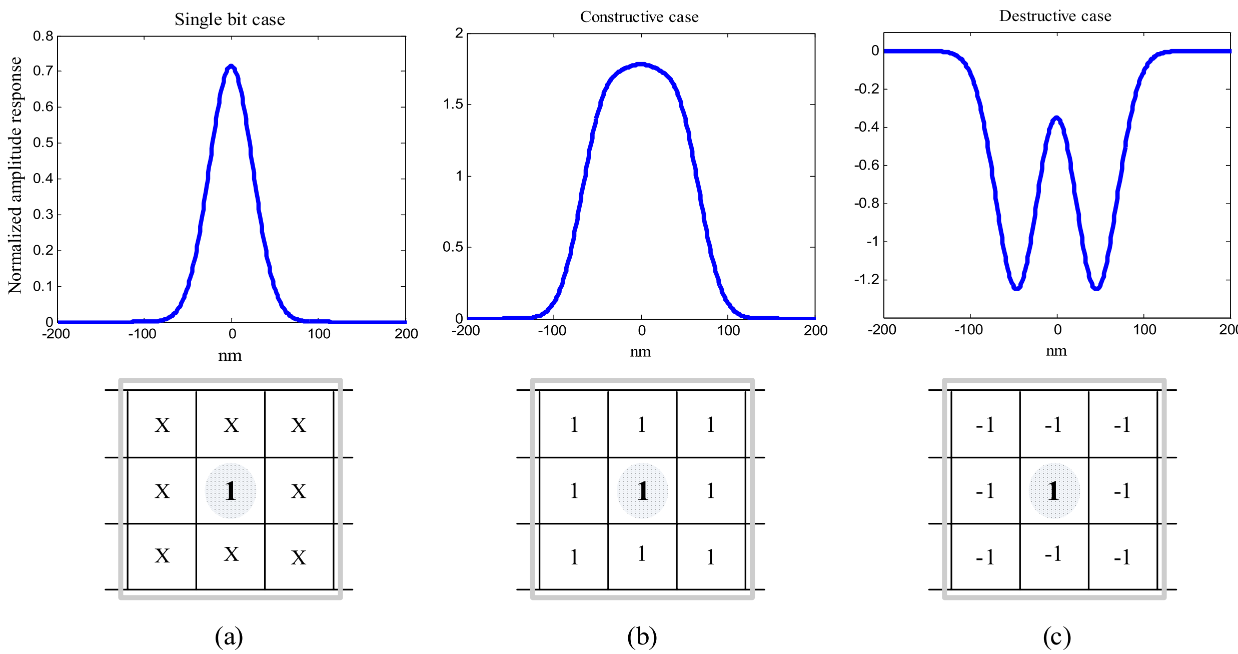

Fig. 1 Examples of the readback signal of (a) the single bit case, where 'X' denotes no recorded bit, (b) the constructive interference case when the bit "1" is surrounded by all 1's, and (c) the destructive interference case when the bit "1" is surrounded by all −1's. All readback signals are generated based on the channel model in Fig. 2 without noise.

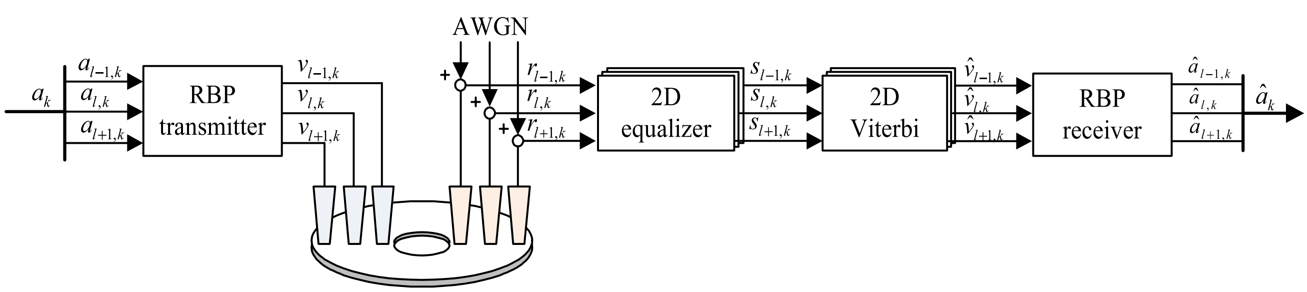

Fig. 2 A BPMR channel model with the RBP scheme.

scheme. A binary input sequence $a_k \in \{\pm 1\}$ with bit period T_x is split into three tracks, namely, the $(l-1)$th upper track, the lth center track, and the $(l+1)$th lower track. Then, these three data tracks are fed into the RBP transmitter block to search for the best 3-track data pattern before recording the three data sequences $[v_{l-1,k}, v_{l,k}, v_{l+1,k}]$ on the three adjacent tracks $(l-1)$, (l), and $(l+1)$, respectively.

The readback signal from the kth data bit on the lth track can be expressed as [6], [7]

$$
\begin{aligned}
r_{l,k} &= v_{l,k} \otimes h_{l,k} + n_{l,k} \\
&= \sum_{n} \sum_{m} h_{m,n} v_{l-m,k-n} + n_{l,k}
\end{aligned}
\tag{1}
$$

where $v_{l,k}$'s are the recorded bits, $h_{m,n}$'s are the 2D channel response coefficients, m and n represent the indices of the bit islands in the along-track and the across-track directions, $\otimes$ 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 2D channel response coefficients $\{h_{m,n}\}$ 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.,

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

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, $\{m,n\} \in (-L, \ldots, 0, \ldots, L)$, $2L+1$ is the length of the 2D channel response, and L is an integer. Generally, L should be large enough to guarantee that the tail amplitude of $P(x,z)$ is small (here, we use $L=1$ for simplicity). In addition, this paper considers the 2D Gaussian pulse response of the form [6], [7]

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

where $A = 1$ is assumed to be the peak amplitude of the 2D Gaussian 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, and $c = 1/2.3548$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian pulse [6]. Additionally, we assume that $\Delta_x = \Delta_z$, and it is modeled as a truncated Gaussian probability distribution function with zero mean and σ_j^2, where σ_j is specified as the percentage of bit period T_x.

Next, the readback data sequence $\{r_{l,k}\}$ is equalized by a 2D equalizer to obtain the data sequence $\{s_{l,k}\}$, which is then fed into the 2D Viterbi detector to determine the most likely data sequence $\{\hat{v}_{l,k}\}$ [6]. Finally, the RBP receiver block rearranges the data sequence $\{\hat{v}_{l,k}\}$ with the help of buffer memory to obtain an estimated input sequence, $\hat{a}_k$. Specifically, the data sequence $\{\hat{v}_{l,k}\}$ in each track will be shifted back to its original position to obtain $\{\hat{a}_{l,k}\}$ according to the number of shifts stored in the buffer memory that is received from the RBP transmitter block.

3. Proposed Scheme

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 $(l+1)$. Additionally, we also consider the BPMR medium with two guard bands (i.e., nonmagnetic tracks) for the two outer tracks $(l-2)$ and $(l+2)$ as the baseline. Hence, the three data tracks $[v_{l-1,k}, v_{l,k}, v_{l+1,k}]$ 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). It should be pointed out that the readback signal from the lth track has the ITI effect from the tracks $(l-1)$ and $(l+1)$, whereas that from the tracks $(l-1)$ and $(l+1)$ experiences the ITI effect merely from the lth track.

Because the severity of 2D interference relies on both the readback waveform of the detected bit and the value of its surrounding bits, we propose a simple RBP scheme by rearranging the data bits before recording so as to avoid some data patterns that often cause an error at the data recovery process. Before explaining the RBP scheme, let us consider the channel model in Fig. 2 without any noise, and define the 3-by-3 window 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 shown in Fig. 3. Then, we analyze the signal amplitude of the detected bit for different data patterns within the 3-by-3 window.

We first look at the "single bit" case where only one (isolated) bit is recorded on the medium as demonstrated in Fig. 1(a), where 'X' represents no recorded bit. Generally, the 2D interference can be classified into two cases, namely constructive and destructive interferences. Here, we use the readback waveform of the single bit case as a *reference* to determine if the 2D interference is constructive or destructive. Specifically, given the same detected bit, the 2D interference is said to be constructive if the signal amplitude of the detected bit is larger than that of the single bit case, as depicted in Fig. 1(b) for example. On the other hand, the 2D interference is destructive if the signal amplitude of the detected bit is smaller than that of the single bit case. In practice, when the destructive interference occurs in the readback signal, it could easily cause an error in the data recovery process, depending on how severe it is. For instance, Fig. 1(c) depicts the readback waveform that encounters the severe destructive interference, where in this case the detector could not detect the bit "1" reliably.

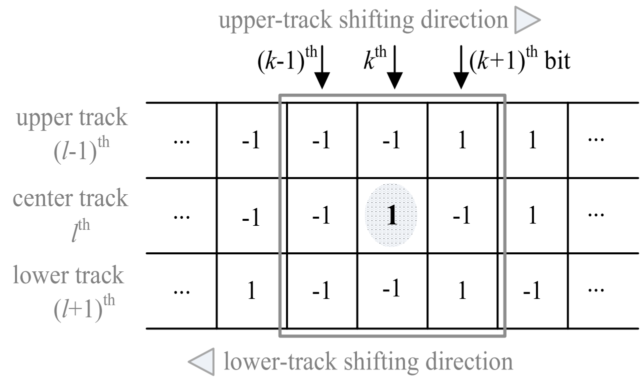

Fig. 3 A simple RBP scheme, where the lth center track is fixed, and the $(l-1)$th upper track and the $(l+1)$th lower track are circularly shifted to the right and to the left, respectively, to create all possible 3-track data patterns.

Next, within the 3-by-3 window, we define the *weight* to determine the severity of 2D interference. Based on our study, it is found that the weight value can be either positive or negative number, depending on whether the 2D interference is constructive or destructive. As a consequence, given the kth detected bit on the lth center track, the weight of the ith data pattern, i.e., $[a_{l-1,k-1}, a_{l-1,k}, a_{l-1,k+1}, a_{l,k-1}, a_{l,k}, a_{l,k+1}, a_{l+1,k-1}, a_{l+1,k}, a_{l+1,k+1}]$, denoted as W_i, is defined as

$$W_i = \begin{cases} Y_i - Y_s, & Y_i > 0 \text{ and } Y_s > 0 \\ |Y_i| - |Y_s|, & Y_i < 0 \text{ and } Y_s < 0 \\ -(Y_i + |Y_s|), & Y_i > 0 \text{ and } Y_s < 0 \\ -(|Y_i| + Y_s), & Y_i < 0 \text{ and } Y_s > 0 \end{cases} \tag{4}$$

where Y_i and Y_s are the peak signal amplitude of the detected bit from the ith data pattern and the single bit case, respectively. Based on (4), there are 512 weights for all possible data patterns within the 3-by-3 window, as listed in Table 1 for example.

3.1 How the RBP Algorithm Works

The detail on how the RBP scheme works can be explained as the following steps.

1) Given the three data tracks $[a_{l-1,k}, a_{l,k}, a_{l+1,k}]$, we move the 3-by-3 window (centered at the lth center track) from the beginning to the end of the center track. For each time step T_x the window is moved, we compute the weight and accumulate it until the window is at the end of the track so as to obtain the *total* weight.

Table 1 The weight of some data patterns within the 3-by-3 window.

Pattern	Upper track, $(l-1)$th			Center track, lth			Lower track, $(l+1)$th			Weight
index, i	$(k-1)$th	kth	$(k+1)$th	$(k-1)$th	kth	$(k+1)$th	$(k-1)$th	kth	$(k+1)$th	W_i
1	−1	−1	−1	−1	−1	−1	−1	−1	−1	1.1255
2	1	−1	−1	−1	−1	−1	−1	−1	−1	1.0298
3	−1	1	−1	−1	−1	−1	−1	−1	−1	0.4947
4	1	1	−1	−1	−1	−1	−1	−1	−1	0.3991
5	−1	−1	1	−1	−1	−1	−1	−1	−1	1.0298
...	...	...	...	...	...	...	...	...	...	...
17	−1	−1	−1	−1	1	−1	−1	−1	−1	−1.1255
18	1	−1	−1	−1	1	−1	−1	−1	−1	−1.0298
19	−1	1	−1	−1	1	−1	−1	−1	−1	−0.4947
...	...	...	...	...	...	...	...	...	...	...
254	1	−1	1	1	1	1	1	1	−1	0.3991
255	−1	1	1	1	1	1	1	1	−1	0.9341
256	1	1	1	1	1	1	1	1	−1	1.0298
257	−1	−1	−1	−1	−1	−1	−1	−1	1	1.0298
258	1	−1	−1	−1	−1	−1	−1	−1	1	0.9341
259	−1	1	−1	−1	−1	−1	−1	−1	1	0.3991
...	...	...	...	...	...	...	...	...	...	...
494	1	−1	1	1	−1	1	1	1	1	−0.4947
495	−1	1	1	1	−1	1	1	1	−1	−1.0298
496	1	1	1	1	−1	1	1	1	−1	−1.1255
...	...	...	...	...	...	...	...	...	...	...
508	1	1	−1	1	1	1	1	1	1	1.0298
509	−1	−1	1	1	1	1	1	1	1	0.3991
510	1	−1	1	1	1	1	1	1	1	0.4947
511	−1	1	1	1	1	1	1	1	1	1.0298
512	1	1	1	1	1	1	1	1	1	1.1255

2) Next, we fix the center track and then circularly shift the upper track to the right or the lower track to the left (see Fig. 3) to create all possible 3-track data patterns. For each 3-track data pattern, we perform a similar procedure (step 1) to compute the total weight.
3) Finally, the number of shifts used in both the upper and the lower tracks that yields the *maximum* total weight will be stored in the memory, which will be used to shift the data bits $[\hat{v}_{l-1,k}, \hat{v}_{l,k}, \hat{v}_{l+1,k}]$ back to their original positions in the RBP receiver block. Note that the 3-track data pattern with the maximum total weight will cause the least destructive effect of 2D interference in the readback signal.

In this paper, we present three approaches to compute the total weight. The first approach denoted as "Approach 1" is to sum all weights (both negative and positive numbers) so as to accumulate both the destructive and constructive effects. The second approach referred to as "Approach 2" will sum only the positive weight such that only the constructive effect is considered. Finally, the last approach denoted as "Approach 3" is to sum only the negative weight so as to take merely the destructive effect into account.

Generally, the RBP scheme consumes large processing time, especially when the 3-track data sequence is long. However, such large processing time can be reduced by dividing the 3-track data sequence into many small portions. To simplify the discussion, this paper considers the case where one data sector $\{a_k\}$ consists of 4032 bits. Thus, after a 4032-bit data sector is split into three tracks $[a_{l-1,k}, a_{l,k}, a_{l+1,k}]$, each with $L_t = 1344$ bits, we divide the 3-by-1344 data array into n_p portions, each with a 3-by-n_b data array, where $n_b = L_t/n_p$ is the portion length. Although this splitting technique helps reduce the processing time, it requires the additional memory amount of

$$2 \times n_p \times \lceil \log_2(n_b) \rceil \quad \text{(bits)}, \tag{5}$$

where $\lceil u \rceil$ is the smallest integer greater than or equal to u, for one data sector to store the number of shifts used in the upper and the lower tracks, which will be employed in the RBP receiver block.

4. Simulation Results

We test the proposed RBP scheme in the BPMR system depicted in Fig. 2, where the bit period T_x and the track pitch T_z are 18 nm (i.e., approximately equal to an areal density of 2 Tb/in^2 if there is no guard band), the along-track PW_{50} is 19.4 nm, and the across-track PW_{50} is 24.8 nm [6], [7]. A signal-to-noise ratio (SNR) is defined as

$$\mathrm{SNR} = 20\log_{10}\left(\frac{V_p}{\sigma}\right), \tag{6}$$

in decibel (dB), where $V_p = 1$ is assumed to be the peak amplitude of the readback signal. The 2D 3-by-3 target and the 2D 3-by-7 equalizer are designed based on a minimum mean-squared error (MMSE) approach [6], [8] at the SNR required to achieve a bit-error rate (BER) of 10^{-4}. In the simulation, each BER is computed based on a minimum number of 500 error bits. Again, each 4032-bit data sector will be written into three adjacent tracks $(l-1)$, (l) and

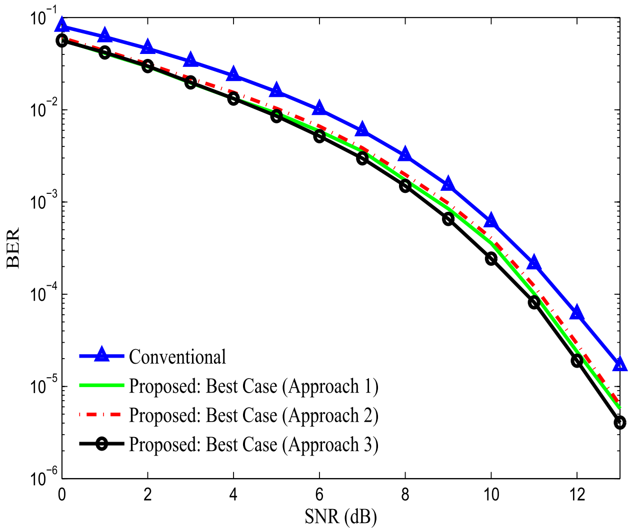

Fig. 4 BER performance of different schemes at $T_x = T_z = 18$ nm and $\sigma_j = 0\%$.

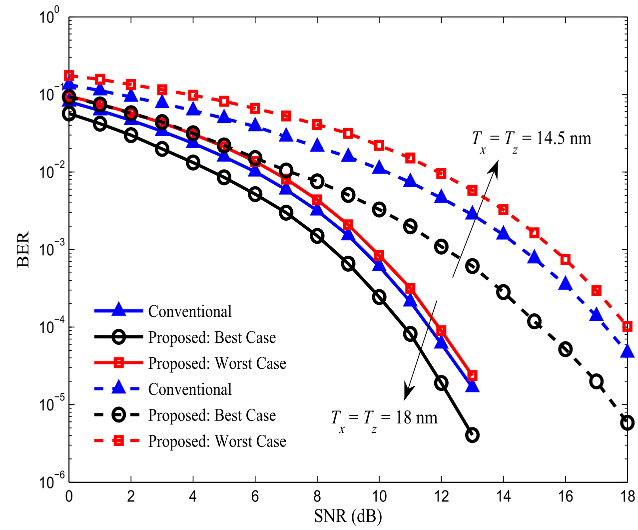

Fig. 5 BER performance of different schemes at $T_x = T_z = 18$ nm and $T_x = T_z = 14.5$ nm with $\sigma_j = 0\%$.

$(l + 1)$, with the two guard bands at the tracks $(l - 2)$ and $(l + 2)$. To reduce the processing time, we divide the 3-by-1344 data array into $n_p = 21$ portions (i.e., the portion length is $n_b = 1344/21 = 64$ bits).

Figure 4 compares the BER performance of different RBP schemes at $T_x = T_z = 18$ nm and no position jitter noise (i.e., $\sigma_j = 0\%$), where the curve labeled as "Conventional" represents the conventional system (without 2D coding), and that labeled as "Best Case" denotes the system using the RBP scheme with the *maximum* total weight. Apparently, all RBP approaches perform better than the conventional system. In addition, Approach 3 provides the best performance followed by Approach 1 and Approach 2. This might be because some severe destructive weights are cancelled out by some constructive weights considered in the Approach 1 and Approach 2. Thus, unlike Approach 3, the best data pattern in Approach 1 and Approach 2 may still contain some severe destructive data patterns. As a result, from now on, we will consider only Approach 3 to investigate the performance of the proposed RBP scheme.

Figure 5 illustrates the BER performance of different schemes at both $T_x = T_z = 18$ nm and $T_x = T_z = 14.5$ nm (i.e., approximately equal to an areal density of 3 Tb/in^2 if there is no guard band) without position jitter noise, where the curve labeled as "Worst Case" represents the system using the RBP scheme with the *minimum* total weight. It is clear that when the recording density is low (i.e., when $T_x = T_z = 18$ nm), only small performance gain can be obtained from the "Best Case" if compared to other schemes. Specifically, the "Best Case" can provide a performance gain of 0.9 dB over the conventional system† at BER = 10^{-4}. Nevertheless, a large performance gap can be achieved when the recording density is increased (i.e., when $T_x = T_z = 14.5$ nm). Specifically, the "Best Case" performs better than the conventional system and the "Worst Case" by about 2.3 dB and 3 dB at BER = 10^{-4}, respectively.

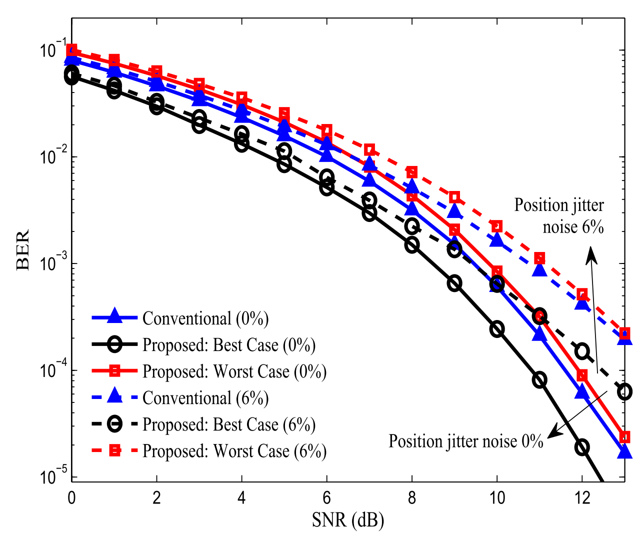

Fig. 6 BER performance of different schemes at $T_x = T_z = 18$ nm with 0% and 6% position jitter noise.

Figure 6 depicts the BER performance of different schemes at $T_x = T_z = 18$ nm with 0% and 6% position jitter noise. Note that the percentage inside the parenthesis in Fig. 6 indicates the percentage of the position jitter noise used to generate each curve. Apparently, the "Best Case" performs better than the others at $\sigma_j = 0\%$ (no position jitter noise). In addition, when the position jitter noise is increased to $\sigma_j = 6\%$, the "Best Case" still provides more than 1.5 dB and 1.6 dB gain at BER = 10^{-4} over the conventional system and the "Worst Case," respectively. Clearly, the performance of all systems gets worse when the position jitter noise is increased.

We also compare the performance of different schemes

†Practically, the performance of the conventional system always lies between that of the "Best Case" and the "Worst Case."

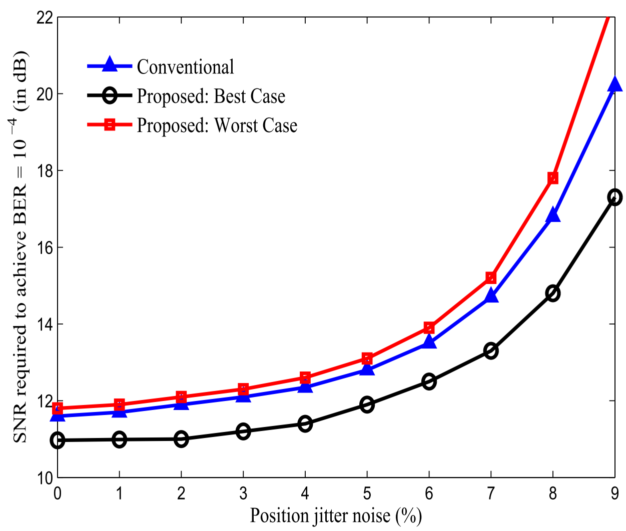

Fig. 7 Performance comparison of different schemes at $T_x = T_z = 18$ nm for various position jitter noise amounts.

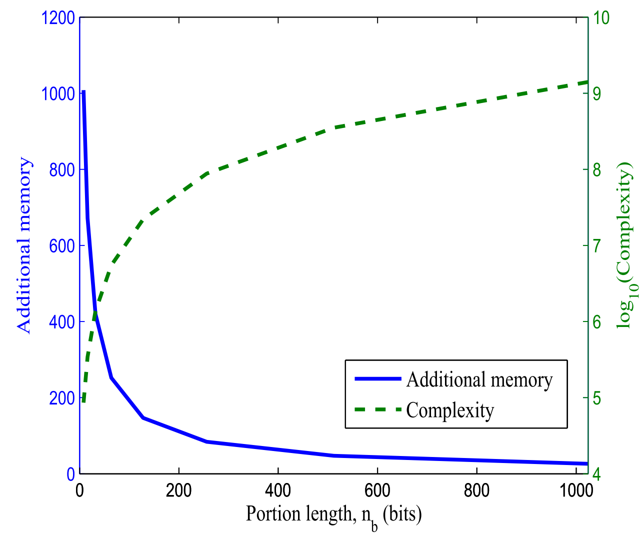

Fig. 8 The memory requirement and the complexity of the RBP scheme as a function of portion lengths.

at $T_x = T_z = 18$ nm for various position jitter noise amounts in Fig. 7, by plotting the SNR required to achieve BER = 10^{-4} as a function of position jitter noise amounts. It is evident that the "Best Case" performs better than other schemes for all position jitter noise levels. Additionally, a large performance gap can be obtained from the "Best Case" if compared to the others, especially when the position jitter noise is high.

Furthermore, we investigate the complexity of the RBP scheme by varying the portion length (n_b) used to divide the 3-track data sequence. In this work, we define the complexity as the total number of shifts used to generate all possible data patterns. Hence, the complexity, C, of the RBP scheme can be computed from

$$C = n_u \times n_l \times n_w \times n_p, \tag{7}$$

where n_u and n_l are the maximum number of possible shifts for the upper and the lower tracks, respectively, and n_w is the total number of shifts for the 3-by-3 window. In general, n_u, n_l and n_w are all equal to n_b. Therefore, the proposed RBP scheme will have the total complexity of $C = n_p \times n_b^3$.

Figure 8 displays the memory requirement and the complexity of the RBP scheme as a function of the portion lengths. Apparently, the larger the portion length, the lower the memory amount, and the higher the complexity. For instance, Table 2 demonstrates the memory requirement and the complexity of the RBP scheme in details, when $L_t = 1344$ is used for a 4032-bit data sector. Again, low additional memory requirement can be obtained at the expense of increased complexity. Accordingly, one needs to tradeoff between the additional memory requirement and the complexity so as to achieve a good performance gain obtained from the RBP scheme.

Table 2 The memory requirement and the complexity of the RBP scheme at different portion lengths (with $L_t = 1344$ bits).

Portion length n_b	Number of portions n_p	Complexity $n_p\, n_b^3$	Additional memory $2\, n_p \lceil \log_2(n_b) \rceil$
8	168	86016	1008
16	84	344064	672
32	42	1376256	420
64	21	5505024	252
128	10.5	22020096	147
256	5.25	88080384	84
512	2.625	352321536	47.25
1024	1.3125	1409286144	26.25

5. Conclusion

At high recording densities, the 2D interference is very severe in the BPMR system, which can be considered as a major cause of performance degradation. Therefore, this paper proposed the RBP scheme to alleviate the 2D interference. The basic idea is to avoid the destructive data patterns (i.e., the data pattern that easily causes an error at the data recovery process) before writing the pre-patterned data onto a medium. Simulation results show that the proposed RBP scheme can help improve the system performance, especially when the recording density is high and/or the position jitter noise is severe. Unlike the existing 2D coding scheme, the proposed RBP scheme can provide a good performance gain without any redundant bit at the expense of using more buffer memory. Consequently, all advantages gained by the proposed RBP scheme need to be balanced against the increased processing time and memory amount. As a result, more research work is required so as to develop the efficient RBP scheme that can performs rapidly and requires low additional memory.

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