Soft-Output Decoding Approach of 2D Modulation Codes in Bit-Patterned Media Recording Systems

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PAPER

Soft-Output Decoding Approach of 2D Modulation Codes in Bit-Patterned Media Recording Systems

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SUMMARY The two-dimensional (2D) interference is one of the major impairments in bit-patterned media recording (BPMR) systems due to small bit and track pitches, especially at high recording densities. To alleviate this problem, we introduced a rate-4/5 constructive inter-track interference (CITI) coding scheme to prevent the destructive data patterns to be written onto a magnetic medium for an uncoded BPMR system, i.e., without error-correction codes. Because the CITI code produces only the hard decision, it cannot be employed in a coded BPMR system that uses a low-density parity-check (LDPC) code. To utilize it in an iterative decoding scheme, we propose a soft CITI coding scheme based on the log-likelihood ratio algebra implementation in Boolean logic mappings in order that the soft CITI coding scheme together with a modified 2D soft-output Viterbi algorithm (SOVA) detector and a LDPC decoder will jointly perform iterative decoding. Simulation results show that the proposed scheme provides a significant performance improvement, in particular when an areal density (AD) is high and/or the position jitter is large. Specifically, at a bit-error rate of 10^{-4} and no position jitter, the proposed system can provide approximately 1.8 and 3.5 dB gain over the conventional coded system without using the CITI code at the ADs of 2.5 and 3.0 Tera-bit per square inch (Tb/in^2), respectively.

key words: *bit-patterned media recording, log-likelihood ratio, modulation code, two-dimensional interference*

1. Introduction

To fulfill an increasing demand for digital data storage, a recording density of future storage systems needs to be enhanced. As a conventional perpendicular magnetic recording technology has physical and engineering limitations, it cannot support an ultra-high storage capacity. Bit-patterned media recording (BPMR) is one of the solutions for future recording technologies, whose areal density (AD) can exceed 1 Tera-bit per square inch (Tb/in^2) [1]–[4]. In BPMR, each data bit is recorded on a single domain magnetic island surrounded by non-magnetic material. To achieve high AD, the data bit islands in both the along-track and across-track directions must be moved closer, leading to an increase of two-dimensional (2D) interference. Moreover, the BPMR challenges also include media noise arising from island position jitter and island size fluctuations in both the along-track and across-track directions [5], track mis-registration (TMR) resulting from the misalignment between the center of the read head and that of the main track [6], and written-in errors caused by mis-synchronization of the write clock to the predefined island locations [5].

Practically, the 2D interference, consisting of inter-symbol interference (ISI) and inter-track interference (ITI), is one of the major impairments in BPMR systems [3], which can significantly deteriorate the system performance if precautions are not taken. Thus, there exist many works presented in the literature to alleviate the 2D interference, including [7]–[9] (and references therein). Additionally, we found in [8], [9] that 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. Specifically, given signal amplitude of an isolated bit, the destructive/constructive ITI will decrease/amplify its signal amplitude. Consequently, when the readback signal of the detected bit encounters the destructive ITI (DITI), it could easily cause an error at the data recovery process. Therefore, we introduced a constructive ITI (CITI) modulation code in [8] to prevent the data patterns that lead to the DITI being recorded onto a magnetic medium. The forbidden data patterns will not be allowed for recording, which will guarantee that the BPMR readback signal will not be corrupted by the severe ITI, thus facilitating the data detection process.

In practice, most communication systems employ iterative error-correction codes (ECCs) because they allow reliable operation at low signal-to-noise ratio (SNR) due to their large coding gains [10], [11]. However, since the CITI modulation code operates on a hard decision basis, it cannot be utilized in the iterative decoding scheme that requires the soft information to be exchanged with a channel detector and a low-density parity-check (LDPC) decoder [12].

Therefore, to employ the CITI modulation code [8] in the coded BPMR system, we propose the soft CITI coding scheme based on the log-likelihood ratio (LLR) algebra implementation in Boolean logic mappings [13], [14]. Hence, the soft CITI coding scheme together with a modified 2D soft-output Viterbi algorithm (2D-SOVA) detector [15]–[17] and a LDPC decoder will jointly perform iterative decoding. It will be shown later that the proposed system can enhance the system performance considerably if compared to the system without using the CITI code in iterative decoding, especially when the AD is high and/or the position jitter is large.

The rest of this paper is organized as follows. Section 2

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explains the coded BPMR channel model, and Sect. 3 briefly describes the proposed scheme. Simulation results are given in Sect. 4. Finally, Sect. 5 concludes this paper.

2. Channel Description

Consider the coded BPMR system with the rate-4/5 CITI coding scheme in Fig. 1. A message sequence $u_k \in \{0, 1\}$ of length 3680 bits is encoded by a regular (3, 27) LDPC code [12] to obtain a sequence $a_k \in \{\pm 1\}$ of length 4140 bits, where the parity-check matrix has 3 ones in each column and 27 ones in each row. Then, the sequence a_k is split into four data tracks $\{a_{k,l}\}$, which will be further encoded by the CITI encoder [8] to obtain five data tracks $\{x_{k,l}\}$ before recording them onto a medium.

The readback signal from the k-th data bit on the l-th track can be written as

$$r_{k,l} = \sum\nolimits_n \sum\nolimits_m h_{m,n} x_{k-m,l-n} + n_{k,l}, \tag{1}$$

where $x_{k,l}$'s are the recorded bits, and $n_{k,l}$'s are additive-white Gaussian noise (AWGN) with zero-mean and variance σ_n^2. Practically, $h_{m,n}$'s are the coefficients of the 2D channel response, which are obtained by sampling the isolated island pulse response modeled as the 2D Gaussian pulse response at integer multiples of the bit period T_x and the track pitch T_z according to [3], [4]

$$h_{m,n} = A \exp\left\{-\frac{1}{2b^2}\left[\left(\frac{mT_x + \Delta_x}{\mathrm{PW}_x}\right)^2 + \left(\frac{nT_z + \Delta_z}{\mathrm{PW}_z}\right)^2\right]\right\}, \tag{2}$$

where m and n are the time indices of the bit island in the along-track and across-track directions, $A = 1$ 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 the Gaussian pulse [3], PW_{50} is the pulse width at half of its peak value, Δ_x is the along-track location fluctuation (or position jitter [3]), 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. Here, 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. In addition, $\{m, n\} \in (-L, \ldots, 0, \ldots, L)$, where $2L + 1$ is the pulse length, and L is an integer. Although L should be large enough to assure that the tail amplitude of the Gaussian pulse is small, this paper uses $L = 1$ for simplicity.

At the receiver, the five data tracks $\{r_{k,l}\}$ are detected by an array of five read heads simultaneously (or one read head to detect these tracks one by one with an aid of buffer memory). Then, the sequence $\{r_{k,l}\}$ is equalized by a 2D equalizer followed by a modified turbo equalizer [17], [18], which iteratively exchanges the soft information among a modified 2D-SOVA detector, a soft CITI decoder/encoder, and an LDPC decoder (implemented based on a message passing algorithm [12] with 3 internal iterations). Specifically, after the first global iteration ($N_\mathrm{G} = 1$), the LDPC decoder will feed back the log-likelihood ratio (LLR) of a_k (i.e., λ_k^a) to the soft CITI encoder to produce the LLR of $\{x_{k,l}\}$ (i.e., $\lambda_{k,l}^x$) for the modified 2D-SOVA detector as the prior information. This process performs as many global iterations as needed before the LDPC decoder outputs an estimated message sequence $\hat{u}_k$.

3. Proposed Scheme

Consider the read head reads the data at the l-th track, and the interference in the cross-track direction is limited to the two adjacent tracks $(l-1)$ and $(l+1)$ as illustrated in Fig. 2. In [8], [9], we found that the DITI occurs when the k-th bit of the adjacent tracks differs from that of the l-th center track, i.e., $[x_{k,l-1}, x_{k,l}, x_{k,l+1}]$ is either $[-1, 1, -1]$ or $[1, -1, 1]$. It is very important to note that these patterns may be changed depending on the considered AD. Nevertheless, we found that the ADs of 2.5 and 3.0 Tb/in^2 have the same DITI patterns as stated before. Hence, the rate-4/5 CITI code [8] maps every 4-by-1 data array $[a_{k,l}, a_{k,l+1}, a_{k,l+2}, a_{k,l+3}]$ to a 5-by-1 codeword $[x_{k,l}, x_{k,l+1}, x_{k,l+2}, x_{k,l+3}, x_{k,l+4}]$ as given in Table 1, such that $[x_{k,j}, x_{k,j+1}, x_{k,j+2}]$ is neither $[-1, 1, -1]$ nor $[1, -1, 1]$ for $j \in \{l, l+1, l+2\}$. Additionally, the CITI encoding and decoding processes are performed based on

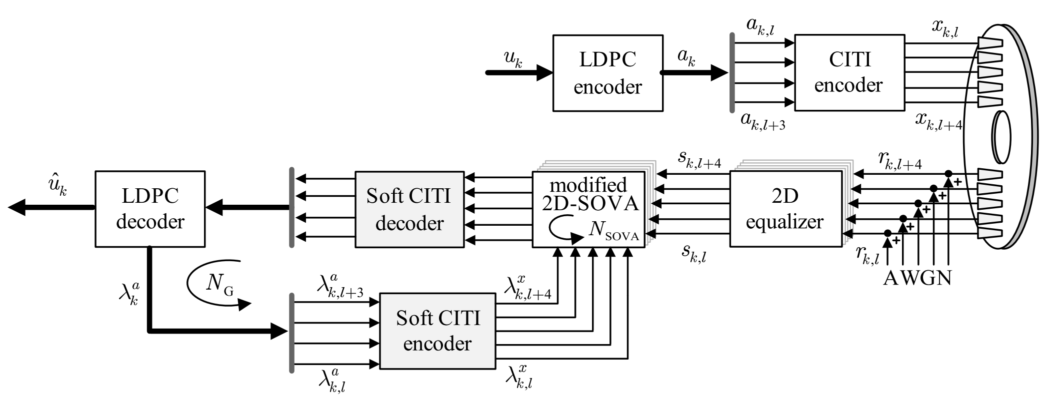

Fig. 1 A coded BPMR channel model with the proposed soft-CITI coding scheme.

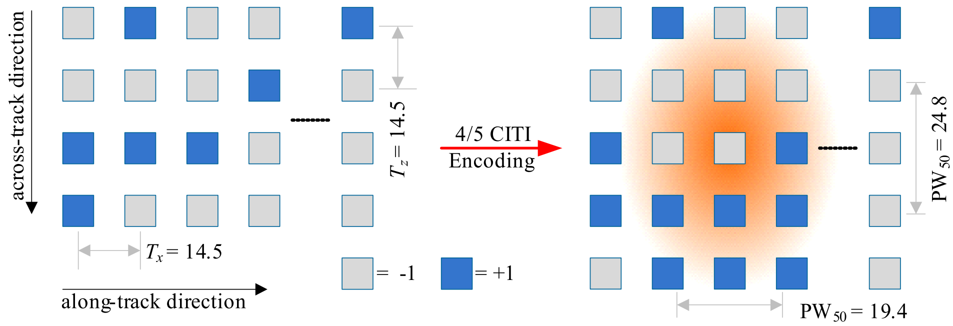

Fig. 2 An example illustration of the proposed rate-4/5 2D CITI modulation encoding scheme and configuration of the regular array islands for 3.0 Tb/in^2 under the isolated island's pulse response.

Table 1 A look-up table for the rate-4/5 2D modulation CITI encoding scheme.

4-bit input data, $\mathbf{a}_{k,l}$				5-bit codeword, $\mathbf{x}_{k,l}$				
$a_{k,l} \rightarrow a_{k,l+3}$				$x_{k,l} \rightarrow x_{k,l+4}$				
−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

the look-up table [8], designed to avoid the data patterns that easily cause the DITI. The results are satisfactory for the uncoded BPMR system; however, since the CITI coding scheme operates on a hard decision basis, it cannot directly be utilized in conjunction with the LDPC code.

Therefore, to employ the CITI code in an iterative decoding scheme, we propose a soft CITI coding scheme that can be performed, based on Boolean logic circuits as shown in Fig. 3. To explain how it works, we denote each set of 4-by-1 input data array as $[a_0, a_1, a_2, a_3]$ and its corresponding 5-by-1 codeword as $[x_0, x_1, x_2, x_3, x_4]$. Hence, from Fig. 3, the outputs of the CITI encoder can be expressed as

$$\begin{aligned} x_0 &= a_0, \\ x_1 &= a_0 a_1 + a_1 a_3 + a_1 a_2 + a_0 a_2 a_3, \\ x_2 &= \bar{a}_0 a_1 + a_1 a_3 + a_1 a_2 + \bar{a}_0 a_2 a_3, \\ x_3 &= a_2 \bar{a}_3 + \bar{a}_0 a_2 + a_1 a_2 + \bar{a}_0 a_1 \bar{a}_3, \\ x_4 &= a_1 \bar{a}_2 \bar{a}_3 + a_1 a_2 a_3 + \bar{a}_1 \bar{a}_2 a_3 + \bar{a}_1 a_2 \bar{a}_3, \end{aligned} \tag{3}$$

where $\bar{a}$ is a complement of a. Similarly, the outputs of the CITI decoder can also be written as

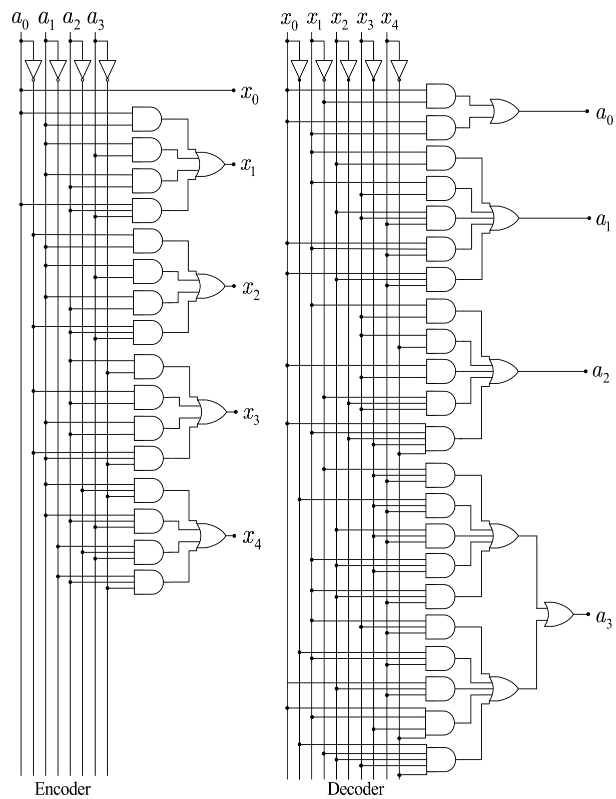

Fig. 3 The rate-4/5 CITI encoder and decoder based on Boolean logic mappings.

$$\begin{aligned} a_0 &= x_0 \bar{x}_1 + x_0 x_1, \\ a_1 &= x_1 x_2 + x_1 x_3 + x_2 x_3 x_4 + x_0 x_1 x_4 \\ &\quad + x_0 x_2 x_4, \\ a_2 &= x_1 x_3 + x_3 \bar{x}_4 + x_0 x_3 + \bar{x}_1 \bar{x}_2 x_3 \\ &\quad + x_0 x_1 \bar{x}_2 \bar{x}_3 \bar{x}_4, \\ a_3 &= \bar{x}_1 \bar{x}_3 x_4 + \bar{x}_0 \bar{x}_3 x_4 + x_2 \bar{x}_3 x_4 + x_1 x_2 \bar{x}_3 \\ &\quad + x_1 x_2 x_4 + x_1 x_3 x_4 + \bar{x}_0 x_1 x_4 + x_0 x_2 x_4 \\ &\quad + x_0 x_1 \bar{x}_3 \bar{x}_4 + \bar{x}_0 \bar{x}_1 x_2 x_3 \bar{x}_4. \end{aligned} \tag{4}$$

Next, let us define the LLR of the bit z_k as

$$\mathrm{LLR}(z_k) = \lambda_k^z = \ln\left(\frac{\Pr[z_k = 0]}{\Pr[z_k = 1]}\right), \tag{5}$$

where ln(·) is a natural logarithm function, and $\Pr[z_k]$ is a probability of z_k [12]. To perform the soft CITI encoding/decoding process, we replace each data sample in (3) and (4) by its corresponding LLR. Then, we apply the technique based on the *min-max* in Boolean logic circuit soft-decision algorithm [13], [14], comprising NOT, AND, and OR gates, to produce the LLR output according to

$$\mathrm{LLR}(\lambda_1\lambda_2) = \mathrm{LLR}(\lambda_1 \text{ AND } \lambda_2) \approx \max(\lambda_1, \lambda_2), \tag{6}$$

$$\mathrm{LLR}(\lambda_1 + \lambda_2) = \mathrm{LLR}(\lambda_1 \text{ OR } \lambda_2) \approx \min(\lambda_1, \lambda_2), \tag{7}$$

$$\mathrm{LLR}(\bar{\lambda}_1) = \mathrm{LLR}(\text{NOT } \lambda_1), \approx -\lambda_1, \tag{8}$$

where λ_1 and λ_2 are the LLR inputs, and $\min(\mathbf{x})$ and $\max(\mathbf{x})$ functions return the smallest and largest value in a vector $\mathbf{x}$, respectively. For example, the LLR of a_0 in (4) can be computed by $\lambda_0^a = \min(\max(\lambda_0^x, -\lambda_1^x), \max(\lambda_0^x, \lambda_1^x))$.

4. Simulation Results

This paper makes a comparison among 1) the conventional uncoded system (i.e., without ECCs) as used in [8], where a rate-4/5 CITI code, five 2D equalizers, and five 2D Viterbi detectors are employed; 2) the conventional coded system without CITI code, where a coded sequence a_k is written onto a single track with random data on adjacent tracks, and one 2D equalizer and one 2D-SOVA detector are used; and 3) the proposed system given in Fig. 1, where five modified 2D-SOVA detectors iterate soft information among them for N_{SOVA} iterations [17] and the iterative decoding is performed for N_{G} global iterations.

We consider the BPMR system in Fig. 1 at the AD of 2.5 Tb/in^2 ($T_x = T_z = 16$ nm) and 3.0 Tb/in^2 ($T_x = T_z = 14.5$ nm), where the along-track PW_{50} is 19.4 nm, and the across-track PW_{50} is 24.8 nm, similar to [3], [8]. Then, we define SNR as

$$\mathrm{SNR} = 10\log_{10}\left(\frac{1}{R\sigma^2}\right), \tag{9}$$

in decibel (dB), where '1' is assumed to be the peak amplitude of the readback signal, and R is an overall code rate of the system. For example, the 2D 3-by-3 symmetric target for the AD of 2.5 Tb/in^2 is given by

$$\text{2D Target} = \begin{bmatrix} 0.02 & 0.20 & 0.02 \\ 0.10 & 1.00 & 0.10 \\ 0.02 & 0.20 & 0.02 \end{bmatrix}, \tag{10}$$

and its corresponding 2D 3-by-7 equalizer are designed based on a minimum mean-squared error approach [3], [8] at the SNR required to achieve the bit-error rate (BER) of 10^{-4}. Notice that the 2D SOVA detector for this 3-by-3 symmetric target utilizes the trellis which has 36 states with 6 parallel branches between any two connected states [3], [8]. Each BER point is computed using as many 3680-bit data sectors

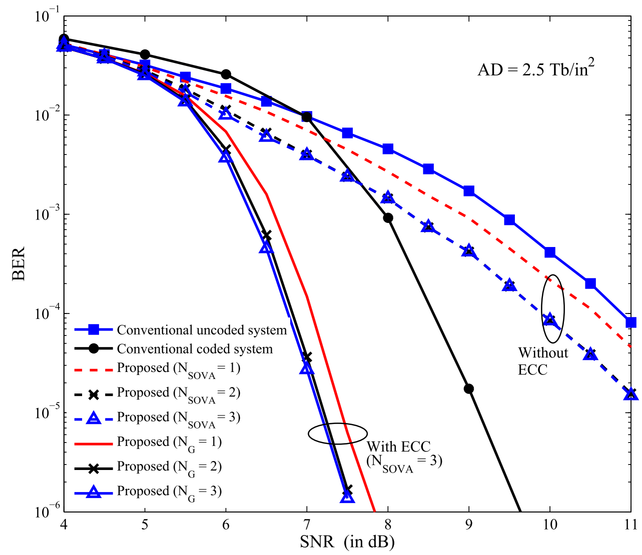

Fig. 4 BER performance of different systems without position jitter at the AD of 2.5 Tb/in^2.

as needed to collect at least 500 erroneous bits, which can provide the sufficient statistics of the result. For instance, at BER $= 10^{-4}$, our simulation transmits the message sequence $\{u_k\}$ of at least 5 million bits into the recorded system.

Figure 4 compares the BER performance of different systems at the AD of 2.5 Tb/in^2 without position jitter, i.e., $\sigma_j/T_x = 0\%$, where $N_{\mathrm{G}} = 1$ denotes the system performance at the output of the LDPC decoder on the first pass. Clearly, without ECCs, the proposed system with $N_{\mathrm{SOVA}} = 3$ still provides a performance gain of about 1 dB at BER $= 10^{-4}$ over the conventional uncoded system. Additionally, a big performance gap can be obtained when utilizing the CITI code in iterative decoding. Specifically, at BER $= 10^{-4}$, the proposed system with $N_{\mathrm{G}} = 3$ and $N_{\mathrm{SOVA}} = 3$ is superior to the conventional uncoded and coded systems for about 4 dB and 1.8 dB, respectively.

Similarly, we also evaluate the performance of different systems without position jitter at a higher AD, e.g., 3.0 Tb/in^2, as illustrated in Fig. 5. In this case, we found that the proposed system performs even better than the other systems. In particular, the proposed system with $N_{\mathrm{G}} = 3$ and $N_{\mathrm{SOVA}} = 3$ yields a performance gain of about 4.3 dB and 3.5 dB over the conventional uncoded and coded systems, respectively. This is because the CITI code prevents the destructive data patterns to be written onto a medium (i.e., the forbidden data patterns will never be recorded), thus reducing the ITI effect [8], [9]. Consequently, using the CITI code in iterative decoding will provide significant performance improvement.

Moreover, to verify that the proposed soft CITI coding scheme can be performed well when it encounters with some media noise (e.g., position jitter), we plot the SNR required to achieve BER $= 10^{-4}$ as a function of position jitter amounts, as shown in Fig. 6, where the position jit-

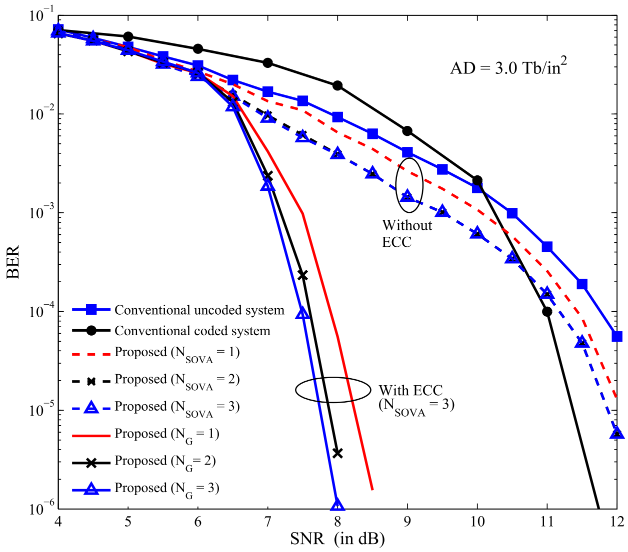

Fig. 5 BER performance of different systems without position jitter at the AD of 3.0 Tb/in^2.

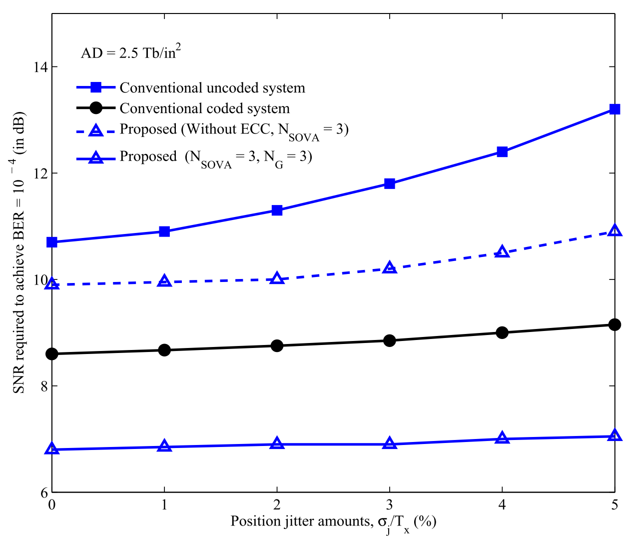

Fig. 6 The SNR required to achieve BER = 10^{-4} with several position jitter amounts at the AD of 2.5 Tb/in^2.

ter amounts σ_j/T_x are varied from 0% to 5%. Again, the proposed system outperforms the other systems, especially when the position jitter is large. Accordingly, it can be implied that the proposed system is worth employing in the coded BPMR system.

5. Conclusion

In this paper, an approach for the soft-decision decoding of the rate-4/5 CITI code has been proposed for BPMR systems, which is based on the LLR algebra implementation in Boolean logic mapping and uses the *min-max* in Boolean logic circuit soft-decision algorithm. Then, we propose to combine the soft CITI code with a modified 2D-SOVA detector and a LDPC decoder so as to jointly perform iterative decoding in the coded BPMR system. Apparently, simulation results show that the system with our proposed soft CITI coding scheme yields a good performance and performs better than the conventional coded system without using the CITI code, especially when an areal density is high and/or the position jitter is large. These significant results additionally facilitate the fact that the ECCs with a rate-4/5 CITI code concatenation are desirable for the BPMR system.

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