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1 author:

Piya Kovintavewat
Nakhon Pathom Rajabhat University

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Investigation of Graph-Based Detection in Iterative Decoding for Bit-Patterned Media Recording

Piya Kovintavewat

Data Storage Technology Research Center, Nakhon Pathom Rajabhat University, Thailand

piya@npru.ac.th

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Abstract. High-density bit-patterned media recording (BPMR) can be obtained by reducing the spacing between data bitislands in both the along- and across-track directions, thus leading to severe intersymbol interference (ISI) and intertrack interference (ITI) because of small bit and track pitches, respectively. Here, we propose to use the graph-based detector, instead of the trellis-based detector, in iterative decoding to combat the ISI and the ITI for a multi-head multi-track BPMR system. Specifically, the readback signal is sent to the graph-based detector before iteratively exchanging the soft information with a decoder. Experimental results indicate that at low to moderate complexity, the proposed scheme outperforms the existing schemes, especially at high recording density.

Introduction

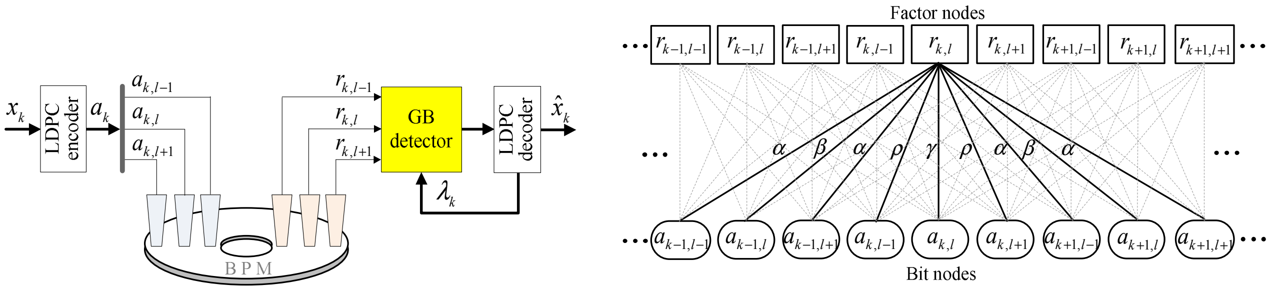
BPMR is one of the solutions for the next generation's hard disk drives because it can achieve a storage capacity up to 4 Tb/in^2 [1]. Unlike the continuous magnetic medium, a data bit in BPMR is stored in a single domain magnetic island surrounded by non-magnetic material. Practically, BPMR encounters the two-dimensional (2D) interference consisting of ISI and ITI, especially at high recording density because of small bit pitch T_x and track pitch T_z.

Several works have recently been proposed to overcome the 2D interference in BPMR [1-6]. For a single-head BPMR system, Nabavi *et al.* [1] proposed a modified Viterbi detector, whose trellis has three parallel branches between any two connected states, to mitigate the ITI. Kalakulak *et al.* [2] presented a zero-corner 2D target with a one-dimensional (1D) equalizer to combat the ITI, and used the 2D Viterbi detector to decode data. The performance of an iterative decoding scheme for BPMR was studied in [3]. In addition, Nabavi *et al.* [4] also introduced a 2D equalizer for a multi-head BPMR system, which performs better than the 1D equalizer at the expense of increased implementation cost. Nevertheless, all these methods process the readback signal from a main track only and treat the ITI as noise, thus yielding poor performance.

To tackle the ITI problem, Myint *et al.* proposed a partial ITI mitigation (PIMM) method [5] for multi-track processing in iterative detection, which utilizes the estimates of the data on the sidetracks to improve the detection on the center track. Also, Hu *et al.* [6] introduced a graph-based (GB) detector for multi-track processing, which has a much lower complexity and a fast parallel structure if compared to the 2D Viterbi detector [2]. However, this paper proposes to employ the GB detector in iterative decoding for a multi-head multi-track BPMR system.

Channel Model

Consider a coded BPMR channel in Fig. 1(a), where we assume that only two adjacent tracks cause most of the ITI. A message sequence $x_k \in \{0, 1\}$ of length 3640 bits is encoded by a rate-8/9 low-density parity-check (LDPC) code [11] and is mapped to a data block of 4095 bits $a_k \in \{\pm 1\}$ with bit period T_x. This data sequence a_k is split into three adjacent tracks $[a_{k,l-1}, a_{k,l}, a_{k,l+1}]$, each with 1365 bits, which will then be written on three adjacent tracks using an array of three write heads. The k^{th} data bit along the l^{th} track, $r_{k,l}$, can be expressed as



(a) (b)

Fig. 1. (a) A coded BMPR channel and (b) the factor graph for the 3×3 channel matrix **H** in Eq. (2).

$$r_{k,l} = \sum_i \sum_m h_{i,m} a_{k-i,l-m} + n_{k,l}\,, \tag{1}$$

where $h_{i,m}$'s are the 2D channel response coefficients, and $n_{k,l}$ is an additive white Gaussian noise with zero mean and variance σ^2. Without the track misregistration [1, 2], a discrete-time 3×3 symmetric channel response matrix generated by a 2D Gaussian pulse response [3] can be written as

$$\mathbf{H} = \begin{bmatrix} h_{k-1,l-1} & h_{k,l-1} & h_{k+1,l-1} \\ h_{k-1,l} & h_{k,l} & h_{k+1,l} \\ h_{k-1,l+1} & h_{k,l+1} & h_{k+1,l+1} \end{bmatrix} = \begin{bmatrix} \alpha & \rho & \alpha \\ \beta & \gamma & \beta \\ \alpha & \rho & \alpha \end{bmatrix}, \tag{2}$$

where γ, β, and $\{\rho, \alpha\}$ are the gain, the ISI coefficient, and the ITI coefficients related to the detected bit $a_{k,l}$. At the receiver, the three readback sequences $[r_{k,l-1}, r_{k,l}, r_{k,l+1}]$ 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). Hence, these three data tracks are fed into a turbo equalizer [3], which iteratively exchanges the soft information between the soft detector and the LPDC decoder.

Graph-Based Detection

The GB detector was proposed in [6] for multi-track recording channels (e.g., BPMR), which exploits the knowledge of the bits from the adjacent tracks in detection process. To do so, the three readback sequences $[r_{k,l-1}, r_{k,l}, r_{k,l+1}]$ are reshaped into a 1D data array with a sequential order before feeding to the GB detector, which employs a message passing algorithm (MPA) [7] over the factor graph designed based on the channel constraint in Eq. (2). Specifically, it consists of two node layers, namely, the factor node representing the noisy channel output $r_{k,l}$, and the bit node representing the input bit, $a_{k,l}$. Thus, the edge between the bit node and the factor node exists if the input bit contributes to the channel output. Therefore, for the 3×3 symmetric channel in Eq. (2), each factor node is connected to 9 bit nodes as shown in Fig. 1(b).

For the GB detection, the factor nodes and the bid nodes exchange the log-likelihood ratio (LLR) information, which can be generated by the sum-product update rule, based on the incoming messages from the connected bit nodes, the received signal, and the channel constraint. Let A^i denote all the bit nodes connected to the i^{th} factor node, and $A^i_{\sim j}$ is equal to A^i excluding the j^{th} bit node. To reduce the complexity, the max-log approximation is utilized to compute the LLR for the i^{th} factor node sent to the j^{th} bit node at the n^{th} iteration according to [6]

$$\varphi^{(n)}_{i\to j} = \max_{A^i:a_j=+1} \left\{ -\frac{|r_i - \hat{r}_i|^2}{N_0} + \sum_{a_k \in A^i_{\sim j},\, a_k=+1} \eta^{(n-1)}_{k\to i} \right\} - \max_{A^i:a_j=-1} \left\{ -\frac{|r_i - \hat{r}_i|^2}{N_0} + \sum_{a_k \in A^i_{\sim j},\, a_k=-1} \eta^{(n-1)}_{k\to i} \right\}, \tag{3}$$

where r_i is the i^{th} received signal sample, and $\hat{r}_i$ is the i^{th} noiseless channel output corresponding to each possible choice of A^i. Then, each j^{th} bit node calculates the LLR for the i^{th} factor node from

$$\eta_{j\to i}^{(n)} = \sum_{k\in R_{\sim i}^{j}} \varphi_{k\to j}^{(n-1)} + \lambda_j , \tag{4}$$

where R^j denotes all the factor nodes connected to the j^{th} bit node, $R_{\sim i}^{j}$ is equal to R^j excluding the i^{th} factor node, and λ_j is the *a priori* information about a_j obtained from the LDPC decoder. After the number of GB iterations (N_{GB}), the GB detector outputs the LLR for the LDPC decoder according to

$$\lambda\left(a_j\right) = \sum_{k\in R^{j}} \varphi_{k\to j}^{(N_{\text{GB}})} + \lambda_j . \tag{5}$$

It should be noted that the complexity of the GB detector is mainly determined by that of the factor node, which is linear with N_{GB} and is exponential with the number of nonzero channel coefficients [6].

Partial ITI Mitigation Detection

In PIMM [5], the three readback sequences $[r_{k,l-1}, r_{k,l}, r_{k,l+1}]$ are sent to three modified 1D soft-output Viterbi algorithm (1D-SOVA) detectors separately. During the iterative decoding, the hard estimates from the LDPC decoder are utilized to compute the partial ITI information in the modified 1D-SOVA detectors, which helps the detection of adjacent tracks in the next turbo iteration. At the end of the process, the input data bits on the three tracks are simultaneously recovered.

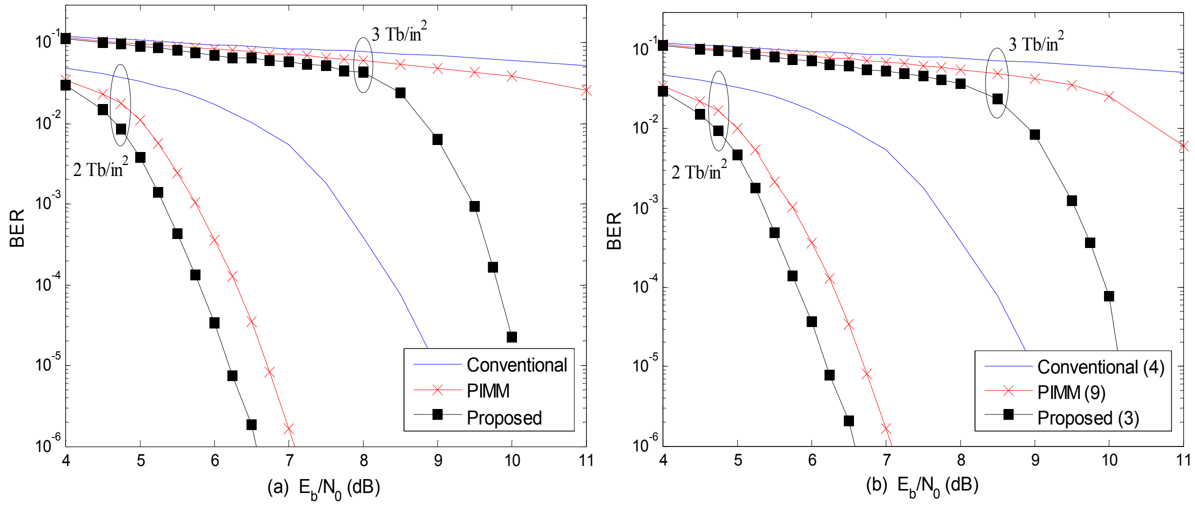
Experimental Results

We consider a rate-8/9 coded system in Fig. 1, where a block of 3640 bits is encoded by a regular (3, 27) LDPC code [7], whose a parity-check matrix has three 1's in each column and 27 1's in each row. The LDPC decoder is implemented based on the MPA with $N_{\text{LDPC}} = 3$ iterations, and the GB detector uses $N_{\text{GB}} = 3$ iterations. The signal-to-noise ratio is defined as E_b/N_0 in dB, where E_b is the energy per bit and $N_0 = 2T_x\sigma^2$. Here, we make a comparison among 1) the proposed scheme in Fig. 1, 2) the PIMM, and 3) the "conventional" scheme where a codeword is written onto a single track (with random data on adjacent tracks) and the 2D SOVA detector [3] is used, whose trellis has 36 states with 6 parallel branches between any two connected states. Consider the 2D Gaussian pulse with the along-track PW$_{50}$ of 19.4 nm and the across-track PW$_{50}$ of 24.8 nm [3]. The 3×3 channel matrix at 2 Tb/in^2 ($T_x = T_z = 18$ nm) and 3 Tb/in^2 ($T_x = T_z = 14.5$ nm) are given by

$$\mathbf{H}_{\text{2Tb}} = \begin{bmatrix} 0.0213 & 0.2321 & 0.0213 \\ 0.0919 & 1 & 0.0919 \\ 0.0213 & 0.2321 & 0.0213 \end{bmatrix} \quad \text{and} \quad \mathbf{H}_{\text{3Tb}} = \begin{bmatrix} 0.0824 & 0.3876 & 0.0824 \\ 0.2125 & 1 & 0.2125 \\ 0.0824 & 0.3876 & 0.0824 \end{bmatrix},$$

Fig. 2(a) compares the bit-error rate (BER) performance of different schemes after $N_{\text{T}} = 5$ turbo iterations. It is clear that the proposed scheme performs better than the conventional scheme and the PIMM, especially when an areal density is high. Specifically, at 2 Tb/in^2 and BER $=10^{-5}$, the proposed scheme can provide a performance gain of 2.8 dB and 0.5 dB, when compared with the conventional scheme and the PIMM, respectively.

Additionally, it is worth comparing the performance of different schemes when they have same complexity. To do so, we define the complexity as the total number of operations (per bit), including the LDPC decoder. It can be shown that the proposed scheme, the PIMM, and the conventional scheme have the total number of additions equal to $18514N_{\text{T}}$, $885N_{\text{T}}$ and $58N_{\text{T}}$, respectively, and have the total number of multiplications equal to $1024N_{\text{T}}$, $1080N_{\text{T}}$ and $43N_{\text{T}}$, respectively. Nonetheless, this paper only considers the multiplication because it has much more complexity than the addition in terms of circuit implementation. Moreover, we assume that current technology can support the total number of multiplications equal to 3 iterations of the proposed scheme, which is approximately



(a) E_b/N_0 (dB)

(b) E_b/N_0 (dB)

Fig. 2. BER performance of different schemes (a) at the 5th turbo iteration, and (b) with same complexity.

equal to 3 and 9 iterations of the conventional scheme and the PIMM, respectively. Fig. 2(b) compares the BER performance of different schemes when they have same complexity. Note that the number inside the parenthesis in Fig. 2(b) indicates the total number of turbo iterations, N_T, used to generate each curve. It is evident that the proposed scheme still performs better than the others, especially at high areal density. This might be because the proposed scheme can combat the severe ITI as opposed to the other schemes.

Summary

The readback signal of the BPRM system inevitably faces with the 2D interference, especially when the recording density is high. In practice, this 2D interference can significantly deteriorate the system performance if precautions are not taken. This paper proposes to employ the GB detector instead of the trellis-based detector in iterative decoding to alleviate the 2D interference. Specifically, the GB detector iteratively exchanges the soft information with the LDPC decoder. Simulation results have demonstrated that for low to moderate complexity, the proposed scheme performs better than the conventional scheme and the PIMM.

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