Complexity Reduction of 2D Detector using 2D Modulation Encoding Constraint in Multi-Track Multi-Head BPMR Systems

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Abstract

The use of two-dimensional (2D) detectors is one of the important ways to cope with the severe 2D interference in bit-patterned magnetic recording (BPMR) systems; however, its complexity still has high complexity. Therefore, this paper proposes the complexity reduction scheme of 2D Viterbi detector in multi-track multi-head BPMR systems. The 2D modulation encoding constraint is utilized to reduce the number of states and branches in the trellis of the detector. The computer simulation results indicate that our proposed detector not only provides the lower complexity but also yields the superior performance, especially at ultra-high areal density.

Keywords: Bit-patterned magnetic recording, 2D modulation code, 2D Viterbi detector.

1. Introduction

To increase an areal density (AD), hard-disk drive (HDD) industry is exploring different recording technologies, such as two-dimensional (2D) magnetic recording (TDMR) [1-3], bit-patterned media recording (BPMR) [4-5], heat-assisted magnetic recording (HAMR) [6], microwave-assisted magnetic recording (MAMR) [7], etc. These technologies were believed that their ADs will be increased beyond 4 Terra-bit per square inch (Tb/in^2).

However, when the AD was increased, the 2D interference consisted of inter-symbol interference (ISI) and inter-track interference (ITI) will be increased in the read channel unavoidably. Therefore, the 2D modulation codes [8-12] were proposed to handle this problem. For example, a constructive inter-track interference coding scheme [9] for a multi-track multi-head BPMR system was introduced to eliminate the data patterns that lead to severe ITI. This coding scheme can guarantee that the obtained readback signal will not be corrupted by the severe ITI, thus facilitating the data recovery process.

Moreover, the multi-track joint 2D detection technique with the help of the array-head reading was also proposed to combat the severe ITI effect by jointly processing the multiple readback signals from the adjacent tracks. The 2D detector can forcefully alleviate the impairments due to the track mis-registration (TMR) and media noise [5, 13]. However, the computational complexity of the 2D detectors is normally too high to practically implement in a real life, even for a few multiple tracks. Therefore, in this paper, we focus on reducing the complexity of the 2D Viterbi detector by using the 2D modulation encoding constraint for the multi-track multi-head (MTMH) BPMR systems. The simulation results show that the modified 2D Viterbi detector not only provides lower complexity but also yields superior performance, especially at ultra-high ADs.

The rest of this paper is organized as follows, Section 2 describes the MTMH BPMR channel model. Then, the reduced complexity 2D Viterbi detector will be explained in Section 3. The simulation results and discussion are provided in Section 4. Finally, the conclusion is given in Section 5.

2. MTMH BPMR Channel Model

We consider a MTMH BPMR channel model with a rate-4/5 encoding technique [9] as shown in Fig. 1. A binary input sequence $a_k \in \{\pm1\}$ with bit period T_x is split into 4 data track sequences, $a_{k,l}$, which are then encoded by the rate-4/5 encoder to obtain 5 data track sequences, $x_{k,l}$ before recording them onto a BPMR medium.

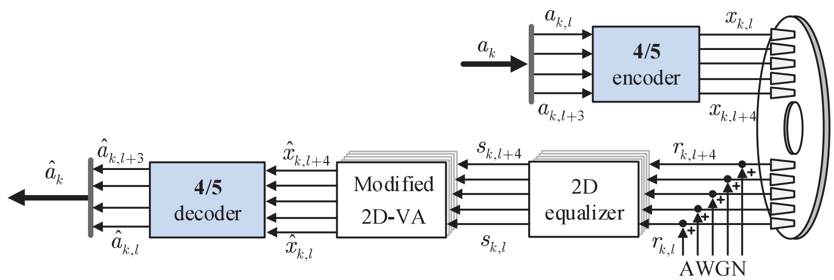

Fig. 1: Block diagram of the multi-track multi-head BPMR channel model with the proposed reduced complexity 2D Viterbi detector.

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

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

where $x_{k,l}$'s are the encoded bits, $\otimes$ is a 2D convolution operator, $h_{m,n}$'s are the 2D channel response coefficients [9], m and n are the time indices of the bit island in the along- and across-track directions, respectively, and $n_{k,l}$ is an additive white Gaussian noise (AWGN) that used as an electronics noise with zero mean and variance σ^2.

In BPMR, $h_{m,n}$'s can be easily 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.,

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

where $P(x,z)$ is the 2D Gaussian pulse response [9], x and z are the time indices in the along- and across-track directions, respectively, $m, n \in (-L, ..., 0, ..., L)$, $2L+1$ is the length of $P(x,z)$, and L is an integer. In general, L should be large enough to ensure that the tail amplitude of $P(x,z)$ is too small enough (in this paper, we use $L = 1$ for simplicity). Additionally, this paper considers the 2D Gaussian pulse response of the form [9]

$$P(x,z) = A\exp\left(\frac{-1}{2c^2}\left[\left(\frac{T_x}{\text{PW}_x}\right)^2 + \left(\frac{T_z}{\text{PW}_z}\right)^2\right]\right), \qquad (3)$$

where $A = 1$ is assumed to be the peak amplitude of the pulse response, $c = 1/2.3458$ is a constant to account for the relationship between PW_{50} and the standard deviation of a Gaussian pulse [9], PW_x is the PW_{50} of the along-track pulse, and PW_z is the PW_{50} of the across-track pulse.

At the receiver, the readback data sequences, $r_{k,l}$, are equalized by the 2D equalizers to obtain the equalized data sequences, $s_{k,l}$, and are then sent to the modified 2D Viterbi detectors to estimate the most likely recorded data sequences, $\hat{x}_{k,l}$. Finally, the rate-4/5 decoder is adopted to decode the 5 data track sequence, $\hat{x}_{k,l}$ into the 4 data track sequences, $\hat{a}_{k,l}$, before grouping them to obtain the estimated input sequence, $\hat{a}_k$. It is very important to note that the performance evaluation is considered from the recorded data sequences because we only need to investigate the performance of the modified 2D Viterbi detector.

3. Modified 2D Viterbi Detector

In a conventional 2D Viterbi detector that is a symbol-based detector, the input symbol and the state of its trellis are defined with the recorded bits from all tracks involved in the readback signal. In this model, the signal contains the contributions from the main track, and the tracks above and below it, the input symbol is modelled with 3 bits from those tracks, resulting $2^3 = 8$ possible input symbols. Given the two delay taps in the target, each state is composed by two symbols. Therefore, the trellis has $2^6 = 64$ states and 8 incoming or outgoing branches at each state. We will see that the complexity of this trellis is too high.

In this work, we consider a modified 2D Viterbi detector where the number of states and branches are reduced by exploiting the constraint of the 2D modulation code. Since the constraint of modulation code does not allow recording two specified bit patterns, i.e., $[-1\ +1\ -1]^T$ and $[+1\ -1\ +1]^T$ on the medium in across-track direction, it does not need to consider the input symbols and the states related to these patterns in the trellis structure. Since there are only 6 possible input symbol, the modified trellis has $6\times6 = 36$ states and 6 incoming or outgoing branches at each state as shown in Fig. 2. The trellis of the modified detector considers all 6 possible recorded bit patterns based on the constraint of the modulation code; therefore, there is no performance loss due to the complexity reduction.

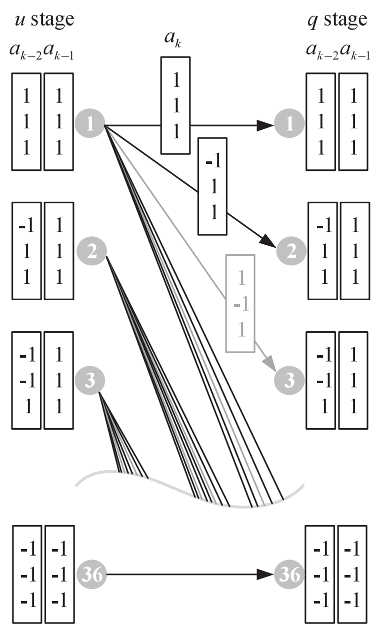

Fig. 2 The trellis diagram of the modified 2D Viterbi detector.

4. Simulation Results

For the performance evaluation, we consider a BPMR system with the AD of 2.0, 3.0, and 4.0 Tb/in^2 by means of setting the bit period and the track pitch to 18, 14.5, and 12.7 nm., respectively. The along- and across-track PW_{50} are considered with 19.4 nm and 24.8 nm, respectively, and each data sequences sector contains 4096 bits. In this paper, a signal-to-noise ratio (SNR) is defined as SNR = $10\log_{10}(1/\sigma^2)$ in decibel (dB). The number of taps in the 2D equalizer is 3×7 for all data track sequences. The modified 2D Viterbi detectors were adopted for the 3 inner tracks while the full complexity 2D Viterbi detectors still be used for the 2 outer tracks e.g., upper- and lower-most tracks.

Fig. 3 compares the bit-error rate (BER) performance of full complexity (Full-2D Viterbi) and modified 2D Viterbi detector (Mod-2D Viterbi) at ADs of 2.0, 3.0, and 4.0 Tb/in^2. Clearly, the proposed 2D Viterbi detector performs slightly better than the conventional 2D Viterbi detector as shown in Fig. 3(a). In addition, we see that the modified 2D Viterbi detector yields better and better performance when the AD is increased as illustrated in Fig. 3(b) and (c), respectively. At the AD of 4.0 Tb/in^2 and BER = 10^{-5}, the modified 2D Viterbi detector can provide the performance gain over the conventional detector for about 4 dB.

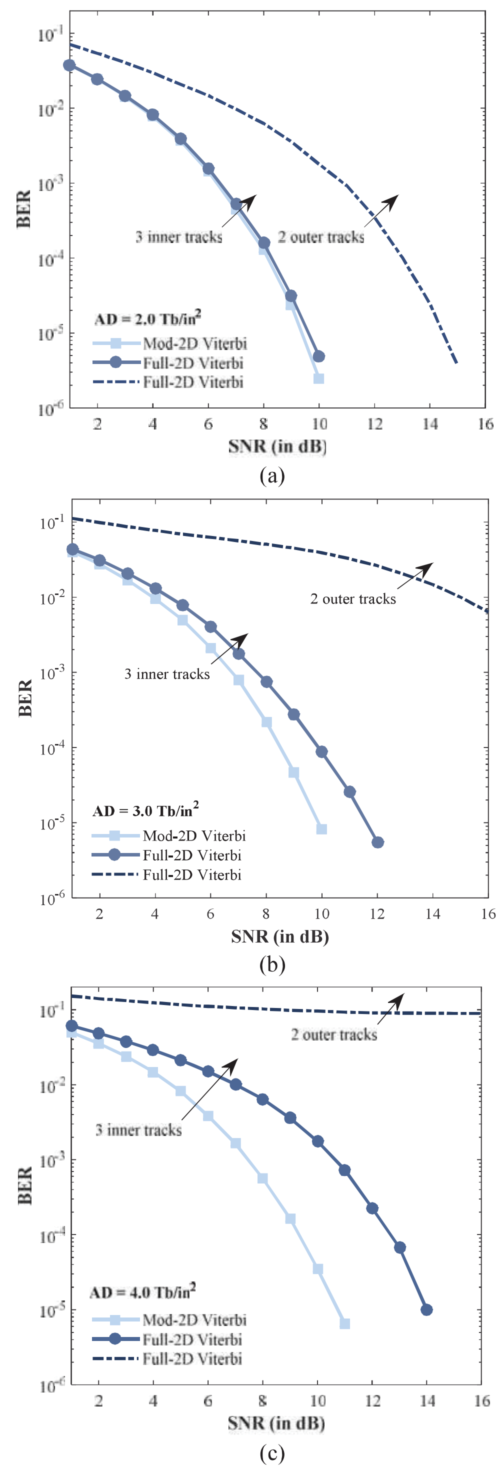

Fig. 3 BER performances of the proposed modified 2D Viterbi detector and conventional Viterbi detector (full complexity 2D Viterbi detector) in various ADs.

5. Conclusion

To cope with the severe ITI and improve the BER performance of the magnetic recording system, this paper proposes the modified 2D Viterbi detector for the multi-track multi-head BPMR system. The encoding constraint of the 2D modulation code is utilized to define the trellis diagram designing. The proposed 2D Viterbi detector not only provides the lower complexity but also yields a better performance. The simulation results show that the modified 2D Viterbi detector can yield the performance gain over the conventional 2D Viterbi detector, especially at ultra-high areal density. However, there are no consideration the media noises such as the position and size fluctuation in this work paper, which is one of the main problem that severely affect to the BPMR system performance.

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References

[1] R. Wood, M. Williams, A. Kavcic, and J. Miles, "The feasibility of magnetic recording at 10 terabits per square inch on conventional media," *IEEE Trans. Magn.*, vol. 45, no. 2, pp. 917–923, Feb. 2009.

[2] A. R. Krishnan, R. R. Redhakrishnan, B. Vasic A. Kavcic, W. Ryan and F Erden "2D Magnetic Recording: Read Channel Modeling and Detection," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 3830–3836, Oct.2009.

[3] K. S. Chan, J. Miles. E. Hwang, B. V. K. VijayaKumar, J. G. Zhu, W. C. Lin, R Negi, "TDMR Platform Simulations and Experiments," *IEEE Trans. Magn.*, vol.45, no. 10, pp. 3837–3843, Oct. 2009.

[4] B. Terris, T. Thomson, andG.Hu, "Patterned media for future magnetic data storage," *Microsyst. Technol.*, vol.13, no. 2, pp. 189–196, Nov. 2006.

[5] S. Navabi, B.V.K.V Kumar, J. G. Zhu., "Modifying Viterbi Algorithm to Mitigate Intertrack Interference in Bit-Patterned Media," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2274–2276, Oct. 2007.

[6] R. Rottmeyer et al., "Heat-assisted magnetic recording," *IEEE Trans. Magn.*, vol. 42, no. 10, pp.2417–2421, Oct. 2006.

[7] Jian-Gang Zhu, "Areal density prediction for microwave SNR and areal density gain in MAMR with segmented media," *IEEE Trans. Magn.*, vol. 50, no. 3, Mar. 2014.

[8] A. Arrayangkool, C. Warisarn, and P. Kovintavewat, "A recorded-bit patterning scheme with accumulated weight decision for bit-patterned media recording," *IEICE Trans. Electron.*, vol. E96-C, no. 12, pp. 1490-1496, Dec. 2013.

[9] A. Arrayangkool, C. Warisarn, and P. Kovintavewat, "A constructive inter-track interference coding scheme for bit-patterned media recording system," Journal of Applied Physics 115, 17B703, 2014.

[10] K. Pituso, C. Warisarn, and D. Tongsomporn, "A soft-5/6 modulation code with iterative ITI subtraction scheme in multireader TDMR systems," *IEEE Trans. Magn.*, vol. 53, no. 11, art ID. 3000904, 2017.

[11] P. Kovintavewat, A. Arrayangkool, and C. Warisarn, "A rate-8/9 2D modulation code for bit-patterned media recording," *IEEE Trans. Magn.*, vol. 50, no. 11, 3101204, Nov. 2014.

[12] K. Pituso, C. Warisarn, D. Tongsomporn, and P. Kovintavewat, "An intertrack interference subtraction scheme for a rate-4/5 modulation code for two-dimensional magnetic recording," *IEEE Magn. Lett.*, vol. 7, art. ID. 4504705, Jul. 2016.

[13] Chang W. and Cruz J R. "Inter-track interference mitigation for bit-patterned magnetic recording," *IEEE Trans. magn.*, vol. 46, no. 11; pp. 3899 – 3908, 2010.