Simplified Multi-track Joint 2-D Viterbi Detection for Bit Patterned Media Recording using Multi-head Array Technolgy

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Abstract: Various detection approaches were proposed to tackle 2-D interference in high density magnetic recording in the literature; however, most of them employed modified 1-D detectors, pseudo 2-D detectors extended from 1-D, instead of a full-fledged multi-track 2-D detection technique to avoid the high computational complexity. In this paper, firstly we study the performance of a full-fledged multi-track joint 2-D Viterbi detector exploiting multi-head array technology for bit patterned media recording (BPMR) system. Due to its high complexity, we also propose a simplified multi-track joint 2-D detector by doing a trade-off between complexity and performance gain. Finally, the performances of joint 2-D detectors are compared with that of conventional 2-D detection technique using multiple single-track detectors.

Keywords— **Viterbi algorithm, Bit pattern media reocording, 2-D Viterbi detection, Multi-track multi-head system, Multi-track detection**

1. Introduction

A bit patterned media recording (BPMR) technology is one of the candidates for future high density magnetic recording storage beyond 1 Tbit/in^2 [1]. In BPMR technology, each bit is recorded on a single-domain magnetic island, theoretically composed by a single magnetic grain, and each island is bordered by non-magnetic regions to alleviate the media noise and the super paramagnetic effect. However, the readback signal from the BPMR media is normally corrupted by a two-dimensional (2-D) interference: inter-symbol interference (ISI) and inter-track interference (ITI) because the areal density is increased by reducing the spacing between islands in along-track and cross-track directions. Without employing a 2-D interference mitigation technique, it leads to a devastating impact on the performance of the data recovery channel.

To tackle the 2-D interference problem, the implementation of a 2-D Viterbi detector is necessary; however, it is impractical due to excessive complexity [2]. In the literature, the efforts have been made on reduced-complexity approaches using modified 1-D detectors [3], pseudo 2-D detectors extension of 1-D detector [4],[5], or 2-D detection techniques using multiple modified detectors with the help of iterative processing [2], [6]-[8]. In addition, the multi-track multi-head technology using a multi-head array has been attracted a lot of attentions from researchers because exploiting multiple signals form the multi-head array can be more robust to errors due to track mis-registration (TMR) and media noise, and moreover, it can improve the performance of data recovery from the 2-D interference channel, especially for alleviating the ITI effects [9], [10]. With the help of the multi-head array, the performance of full-fledged multi-track joint 2-D detection techniques for high density magnetic storage is studied in [2], [8] and [11] and its outperformance over the conventional single-track detection techniques is shown. However, to realize the performance gain from the multi-track joint 2-D detection technique for the high areal density magnetic recording systems such as BPMR system, we need to reduce its complexity until practicable level without paying the significant performance loss because it is still too huge and impractical to implement in reality.

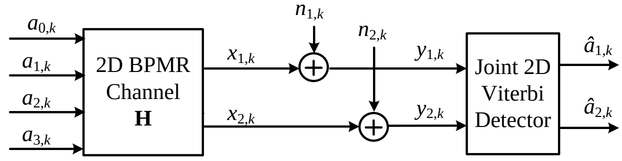

Figure 1. Block diagram of Multi-track multi-head BPMR system.

In this paper, we study the performance of a full-fledged multi-track joint 2-D Viterbi detector for BPMRs multi-track multi-head system using a multi-head array. In order to avoid unmanageable computational complexity, we focus on its application to a BPMR system with two-head array that read the recorded data of two adjacent tracks simultaneously. Furthermore, we also propose a simplified version of multi-track joint 2-D Viterbi detector by making a tradeoff between the computational complexity and the performance gain. Finally, the performances of both multi-track joint 2-D Viterbi detectors are compared with a conventional 2-D detection technique using two single-track 2-D detectors from [4] and [5] for the high areal density of BPMR system.

The remainder of this paper is organized as follows. In Section 2, we describe the BPMR multi-track multi-head recording system model, the full-fledged multi-track joint 2-D Viterbi detector and the proposed simplified multi-track joint 2-D Viterbi detector. Section 3 provides the simulation results and discussion. Finally, conclusions are presented in Section 4.

2. BPMR Multi-track Multi-head System

In this work, we considered a typical 2-D discrete-time channel model of the BPMR's multi-track multi-head system as illustrated in Fig. 1 and in Fig. 2. In the system, four recording sequences $\{a_{l,k}\}$, where $l \in \{0, 1, 2, 3\}$, for the four adjacent tracks are sent to a 2-D BPMR channel. In here, it is important to note that among those sequences, only two sequences $\{a_{1,k}\}$ and $\{a_{2,k}\}$, are considered as the data sequences to be recovered by the detector, but other sequences $\{a_{0,k}\}$ and

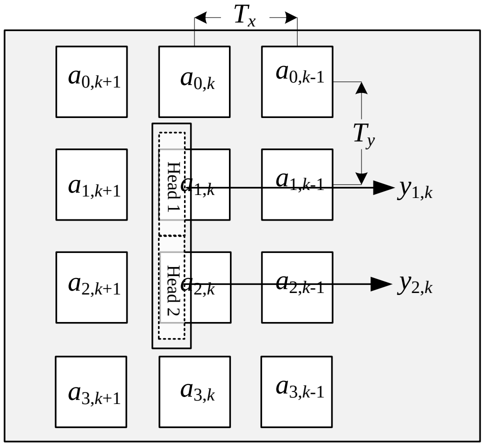

Figure 2. Schematic diagram of a BPMR media using a two-head array.

$\{a_{3,k}\}$, are employed as the ITI effects. At the output of the channel, we assumed that the two readback signals $\{y_{1,k}\}$ and $\{y_{2,k}\}$ are available from the multi-head array composed by two read-sensors that read the recorded bits along the tracks 1 and 2 mainly, as shown in Fig. 2. The readback signal from the k^{th} data bit on the track $l \in \{1, 2\}$, $\{y_{l,k}\}$ is expressed as

$$y_{l,k} = \sum\nolimits_n \sum\nolimits_m h_{n,m} a_{l-n,k-m} + n_{l,k}, \quad (1)$$

where $a_{l,k}$ are the recorded bits at the track l, $h_{n,m}$s are the 2-D BPMR channel response coefficients, $n_{l,k}$ is assumed to be additive white Gaussian noise (AWGN) with a standard deviation $\sigma_{k,l}$, l and n are the indices of the bit islands in the along-track direction, and k and m are the indices of the across-track direction. Assuming that each read-sensor receives the magnetic field from the three adjacent islands on the track under it as well as the islands on the two adjacent tracks and there are no track mis-registration and media noise, each readback signal $y_{l,k}$ is generated with the same discrete BPMR channel represented by a 3x3 channel response matrix, i.e.,

$$\mathbf{H} = \begin{bmatrix} h_{-1,-1} & h_{-1,0} & h_{-1,1} \\ h_{0,-1} & h_{0,0} & h_{0,1} \\ h_{1,-1} & h_{1,0} & h_{1,1} \end{bmatrix}. \quad (2)$$

At the receiver side, both of the readback signal sequences $\{y_{1,k}\}$ and $\{y_{2,k}\}$ are jointly processed by the multi-track joint 2-D Viterbi detector to generate the estimated recorded bit sequences $\{\hat{a}_{1,k}\}$ and $\{\hat{a}_{2,k}\}$.

2.1 Full-fledged multi-track joint 2-D Viterbi detector

In this work, we model a 2-D trellis onto which the full-fledged multi-track joint 2-D Viterbi detector can be employed for estimating multiple tracks simultaneously. Even though the two read-sensors from the head array read the data from two adjacent tracks, they also include the magnetic field contributions from outer two tracks considering the 3x3 channel matrix in (2) as demonstrated in Fig. 2. Therefore,

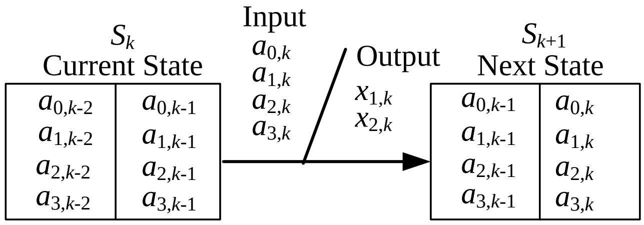

Figure 3. State transition for the full-fledged multi-track joint 2-D detector.

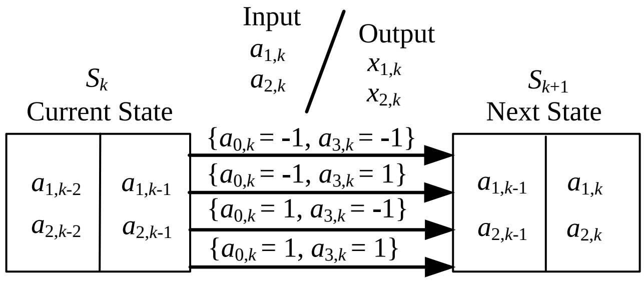

Figure 4. State transition for the simplified multi-track joint 2-D detector.

each input symbol in the trellis is modelled with the recorded bits on four consecutive islands at the same column along the cross track direction and then each state is composed by two symbols similar to [4]. A state transition between the current state and the next state of the resulted 2-D trellis is illustrated in Fig. 3. Finally, the trellis contains $2^{4x2} = 256$ states and each state has $2^4 = 16$ incoming or outgoing branches at each state.

Assuming that both readback signals is corrupted by AWGN with the same standard deviation σ_k, the branch metric for each state transition can be computed using both of two readback signals together, i.e.;

$$\lambda(\xi_k) = -\sum_{l=1}^{2} \left(y_{l,k} - x_l(\xi_k)\right)^2, \quad (3)$$

where $x_l(\xi_k)$ is the noiseless possible channel output of l track for the transition ξ_k, and ξ_k represents the state transition between the current state S_k at time k and the next state S_{k+1} at time $k+1$. For branch metric in (3), both noiseless possible channel outputs are computed with the coefficients of the channel matrix in (2) as

$$x_l(\xi_k) = \sum\nolimits_n \sum\nolimits_m h_{n,m} a_{l-n,k-m} \quad (4)$$

where $a_{l,k}$ are the respective bits from the input and the current state of the transition ξ_k . Here, it is important to notice that the input bits sequence $\{a_{1,k}\}$ and $\{a_{2,k}\}$ are concurrently estimated by the detector even though each state in the trellis is defined by the bits from all four tracks to tackle the full ITI effects of outer tracks $\{0, 3\}$. Finally, the estimated recorded bit sequences $\{\hat{a}_{1,k}\}$ and $\{\hat{a}_{2,k}\}$ are generated by the detector applying Viterbi algorithm over the 2-D trellis.

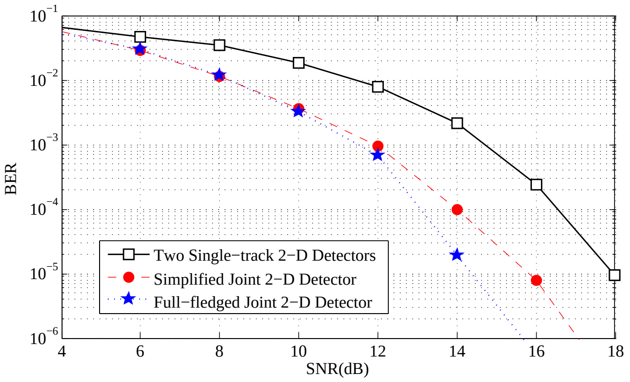

Figure 5. Performance comparison of multi-track joint 2-D detectors for BPMR with areal denstiy 2.5 Tbits/in^2.

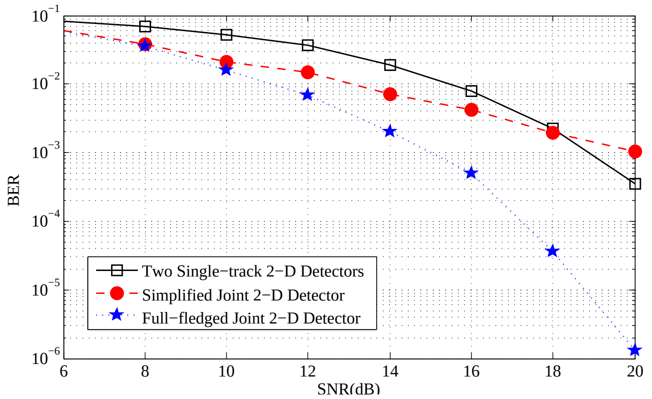

Figure 6. Performance comparison of multi-track joint 2-D detectors for BPMR with areal denstiy 3 Tbits/in^2.

2.2 Simplified multi-track joint 2-D Viterbi detector

Since the complexity of full-fledged joint multi-track 2-D detector is too high to implement practically, we propose a simplified multi-track joint 2-D Viterbi detector without paying a large penalty in terms of the performance. For this proposed detector, the trellis is constructed with the bits from the detecting tracks 1 and 2, i.e., the input symbol is considered with just two bits $a_{1,k}$ and $a_{2,k}$; however, ITI effects from outer two tracks 0 and 3 are alleviated using extended parallel branches between two consecutive states of transition [3], [7]. With a case of two bits per symbol, the simplified trellis contains 16 states and 4 branches at each state. If we assumed that the cornered coefficients of the channel matrix in (2) are negligible small, which happens in most of the cases, the possible noiseless channel outputs of two tracks $l \in \{1, 2\}$ in (3) can be defined ignoring the contributions from the island bits, $a_{0,k+1}$, $a_{0,k-1}$, $a_{3,k+1}$ and $a_{3,k-1}$, as

$$x_1(\xi_k) = \sum_{m=-1}^{1} \sum_{n=0}^{1} h_{n,m} a_{1+n,k-m} + h_{-1,0} a_{0,k}, \quad (5)$$

and

$$x_2(\xi_k) = \sum_{m=-1}^{1} \sum_{n=-1}^{0} h_{n,m} a_{2+n,k-m} + h_{1,0} a_{3,k}. \quad (6)$$

where $a_{l,k}$ are the respective bits from the input and the current state of the transition ξ_k. Since the possible values of $a_{0,k}$ and $a_{3,k}$ in (5) and (6) are $\{\pm 1\}$, there are four parallel branches between each state transition as depicted in Fig. 4. Then, the detector uses the same branch metric computation as (3) for each transition along the trellis in order to to estimate the recorded bit sequences.

3. Simulation Result and Discussion

In this work, we consider a BPMR system with the areal density of 2.5 and 3 Tbits/in^2 by means of setting the bit period and the track pitch to 16 nm and 14.5 nm respectively. The along-track PW50 and across-track PW50 are considered with 19.4 nm and 24.8 nm respectively and each data sequences sector contains 4096 bits. The signal-to-noise ratio (SNR) is defined as $20log10(V_p/\sigma_k)$ where V_p = 1 is the peak value of the readback signal and σ_k is the standard deviation of AWGN. The corresponding channel matrices for the BPMR system with the areal density 2.5 and 3 Tbits/in^2 are

$$\mathbf{H}_{2.5} = \begin{bmatrix} 0.049 & 0.315 & 0.049 \\ 0.152 & 1 & 0.152 \\ 0.049 & 0.315 & 0.049 \end{bmatrix}, \quad (7)$$

and

$$\mathbf{H}_{3} = \begin{bmatrix} 0.082 & 0.388 & 0.082 \\ 0.213 & 1 & 0.213 \\ 0.082 & 0.388 & 0.082 \end{bmatrix}. \quad (8)$$

In this work, the performance of multi-track joint 2-D detectors is compared with a detection technique using multiple single-track 2-D detectors from [4], [5]. Instead of one detector, two single-track 2-D Viterbi detectors are employed to process two readback signals from the head array separately and each detector uses the trellis with 64 states and 16 incoming or outgoing branches at each state.

Firstly, we studied the BER performance of thefull-fledged and simplified multi-track joint 2-D detectors compared with that of multiple single-track 2-D detectors technique for the BPMR system with the areal density 2.5 Tbits/in^2. The simulation result is shown in Fig. 5 where the full-fledged multi-track joint 2-D Viterbi detector is labeled as ”Full-fledged Joint 2-D Detector”, the proposed simplified multi-track joint 2-D Viterbi detector, as ”Simplified Joint 2-D Detector”, and the multiple detectors technique using two signal-track 2-D detectors as ”Two Single-track 2-D Detectors”. It should be noted that, both of joint 2-D Viterbi detectors process two readback signals jointly, but in multiple detector technique, two separate detectors are employed to process two signals independently without exchanging ITI information. According to the simulation result, the multi-track joint 2-D detectors outperform about 3.7 dB and 2 dB than the multiple detectors technique at BER = 10^{-5}; however, the performance of simplified joint detector is inferior about 1.7 dB to that of full-fledged detector as a result of ignoring some ITI effects in branch metric calculation.

We also observed the performance of the multi-track joint 2-D detectors for the BPMR system with the areal density 3 Tbits/in^2. As depicted in Fig. 6, the simplified joint 2-D detector does not perform as well as does in the areal density 2.5 Tbits/in^2. In particular, its performance is inferior to that of the multiple detector technique after SNR level is beyond 18 dB. The primary factor of this performance degradation is because the values of the cornered ITI coefficients of the channel matrix in (8) are not more negligible small and their contributions must be taken into account in the branch metric computation of the proposed simplified detector. Therefore, to alleviate this system inefficiency, the proposed detector needs to design a trellis with all ITI coefficients without increasing the complexity specially for the BPMR system with higher areal density.

Finally, we compared the computation complexity of all 2-D Viterbi detector considered in this work in Table.1. The proposed simplified multi-track joint 2-D detector needs only 256 branch computations for each bit estimation which is obviously less than the full-fledged multi-track joint 2-D Viterbi detector and the technique using two single-track detetors as they need 4096 and 1024 branch computations respectively. Therefore, the proposed method can significantly reduce the computational complexity.

Table 1. Comparison of the computational complexity for each data bit estimation for the 2-D Viterbi Detectors.

Detector Name	Number of States	Number of Branches	Branch computation
Full Joint 2-D Detector	256	16	4096
Simplified Joint 2-D Detector	16	$4\times4=16^*$	256
Multiple 2-D Detectors	$2\times64=128^{**}$	8	1024

*each out going branch has 4 parallel branches.

** each of 2 detectors uses the trellis with 64 states.

4. Conclusion

In this paper, we presented the performance of a full-fledged multi-track joint 2-D Viterbi detector for BPMRs multi-track multi-head system where the detector recovers the recorded bits of two tracks using a two read-sensors array. Then, we proposed the simplified multi-track joint 2-D Viterbi detector that uses a simplified trellis with less complexity. The performances of both multi-track joint 2-D Viterbi detectors are compared with a multiple detectors technique using two single-track 2-D detectors for the two high areal densities of BPMR system. The simulation result shows that the proposed detector outperforms technique using two single-track 2-D detectors but is inferior the full-fledged multi-track joint 2-D detector for the areal density 2.5 Tbit/in2; however, its performance degrades considerably over the higher areal density 3 Tbits/in2. The degradation is because the proposed simplified detector considers only partial ITI effects in the trellis design and the branch insufficient metric computation. In the future work, we will, therefore, modify the trellis design of the proposed simplified detector by taking into account all ITI effects or reducing some ITI effects with the help of the equalization technique and the iterative approach without increasing the complexity significantly. Moreover, we will extend the study of the proposed detector with the full BPMR system including the media noise and other channel characteristics.

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