AIP Advances

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Cite as: AIP Advances **9**, 125240 (2019); https://doi.org/10.1063/1.5130460
Submitted: 08 October 2019 . Accepted: 25 November 2019 . Published Online: 27 December 2019

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Presented: 8 November 2019 • Submitted: 8 October 2019 •
Accepted: 25 November 2019 • Published Online: 27 December 2019

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Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.
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ABSTRACT

In this study, multi-level joint-track readback scheme is proposed for interlaced magnetic recording (IMR) with write synchronization. IMR typically provides an areal density capability (ADC) gain by pre-fixing the recording orders as interlaced and customizing the write configurations for neighboring tracks, such that narrow and wide tracks are interlaced. On the other hand, due to the unbalanced track widths in IMR, readback waveforms by a single wide reader covering two adjacent tracks can be decomposed into four distinguishable levels, when tracks are recorded in a synchronous manner. By taking advantage of the four level (4L) detecting capability, the single reader based dual-track readback (SR-DTR) IMR has a potential to provide a doubled data rate (2X) retrieval. For the feasibility test of the SR-DTR IMR, numerical simulations are conducted for bit-error rate (BER) evaluations by the micro-pixelated magnetic recording channel model. Partial response equalizer and Viterbi detector are modified for 4L readback waveforms, and are investigated with cross-track read offsets under various track and linear densities. BER bathtub investigation results show the feasibility of 2X retrievals by the SR-DTR IMR approach.

I. INTRODUCTION

With dramatic increases of digital data generation[1] and data-driven applications,[2] demand for large capacity and fast data transferring information storage system is ever-increasing. Non-volatile memory technologies continue to evolving for efficient data management with paralleled architecture,[3] however the storage capacity is still limited compared to the hard disk drives (HDDs). On the other hand, advances in HDDs with novel technologies like heat-assisted recording[4] and patterned media manufacturing[5] show potential to further enhance the capacity over multi-terabyte drives,[6] but with limited access rates due to the serialized architecture. Extra efforts also made in the read channel side to provide an areal density capability (ADC) gain, where array-reader based magnetic recording (ARMR) is introduced[7] to enhance the track and linear densities by suppressing and control the inter-track interference by customized joint equalization.[8]

In this study, multi-level joint-track readback scheme is proposed for interlaced magnetic recording (IMR). Typical IMR aims to provide an ADC gain by pre-fixing the recording orders as interlaced and customizing the write configurations for neighboring tracks.[9] Heat-assisted IMR is introduced to achieve extra ADC gain by jointly modulating the optical spot over the high coercivity media.[10] In addition, inter-track interference cancellation[11] and array-reader (AR) schemes[12] are introduced for IMR to reliably retrieve recorded data. Dual-track readback (DTR) IMR with an AR jointly covering neighboring tracks is also investigated for doubling the read data rate but with complicated skew effects by multiple readers.[13] Alternatively, this study focuses on the feasibility of the doubled data rate (2X) dual-track readback with a wide reader, by taking advantage of the interlaced property of the IMR. By synchronized writing of neighboring tracks in an interlaced manner, a single wide reader covering two-tracks jointly is capable of capturing four-level (4L) signals. Compared to the AR-DTR,[13] the proposed single-reader (SR) approach with IMR significantly reduces the processing overheads from multiple readers. In addition, AR has been tried to jointly read multiple tracks together, but works reliably only when the reader-to-reader distance is within the track pitch (TP)[13,14] due to the inevitable skew effects to cover up entire disk drive. On the other hand, multi-level signaling by a single reader is investigated for magnetic recording by pulse width modulation along the down-track,[15] however SR based joint dual-track readback approach is proposed in this study for the first time for our best knowledge. In addition, multi-track joint detector using the two-dimensional (2D) Viterbi detector is investigated for the bit-patterned media recording[16] combining multiple equalizers for reduced complexity, which also differs from the proposed 4L detector with a 4L equalizer.

In order to show the feasibility of the single-reader DTR IMR architecture for 2X retrieval, numerical simulations are conducted with the micro-pixelated magnetic (MPM) channel model,[9] accounting the magnetic granular effects for high track density recording channel. Note that depending on the cross-track read offsets of the reader, balance between widely and narrowly recorded tracks can be broken, so that the centers of the four distinctive levels may not be evenly distributed any more. In this manner, readback waveforms from the wide reader covering the two tracks are synthesized, and evaluated with 4L modified partial response (PR) equalizer and 4L detector. Then, symbol and bit error rates (SERs, BERs) are evaluated with the off-track capabilities (OTCs), and is taken into account to confirm the sensitivity issue with the OTC.

The rest of the paper is organized as follows. Section II introduces the SR-DTR IMR architecture and associated read channel signal processing schemes. Section III evaluates the SER and BER performance of the SR-DTR IMR using the MPM channel model. Finally, Section IV concludes the paper.

II. METHODOLOGY

The SR-DTR IMR channel is illustrated in Fig. 1. Tracks are recorded in an interlaced manner, where even tracks are recorded first with a wide writing condition, and odd tracks are overwritten later with a narrow writing configuration.[17] Note that adjacent tracks are recorded in a synchronous manner for joint multi-level processing, and two adjacent sectors are originated from the same source to take advantage of the joint DTR. Let denote $\mathbf{z}^{2b}$ is the two bit sequences recorded to the two adjacent tracks. During reading, the wide reader captures two adjacent tracks jointly but with different weights by the differentiated relative track widths of the written tracks.

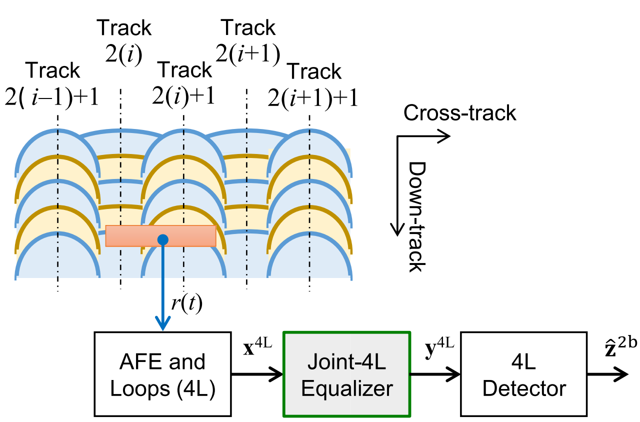

FIG. 1. Block diagram of the four-level (4L) dual-track read (DTR) IMR.

Then, the raw waveform, denoted by $r(t)$, is processed by analog front-end (AFE) and loops to get analog to digital converted (A/D) samples, $\mathbf{x}^{4L}$, which ideally shows four different levels. Later, the samples are equalized associated with the PR target, $\mathbf{y}^{4L}$, and detected by Viterbi detector $\hat{\mathbf{z}}^{2b}$. The 4L signals and their processing will be explained in detail at the following subsections.

A. 4L signal in SR-DTR IMR

As illustrated in Fig. 1, the wide reader captures weighted sum of two adjacent tracks, and the A/D samples $\mathbf{x}^{4L}$ can be decomposed into four levels, depending on the relative track width of the recorded adjacent tracks. For example, the read signal collected by the reader without any noise can be ordered with the recorded j^{th} bits bit of the two tracks $(z_{2(i),j}, z_{2(i)+1,j})$ as $(-, -) < (+, -) < 0 < (-, +) < (+, +)$ in the case of Fig. 1 with wider odd tracks. Corresponding synthesized waveforms and A/D samples are plotted in Fig. 2 for the SR-DTR IMR by the MPM channel model under a typical set up with 1600 kilo-bit-per-inch (kBPI) and 498 kilo-track-per-inch (kTPI), and other configurations will be discussed in detail in Section III. The resulting histograms of A/D samples given the data patterns are plotted in Fig. 3, where histograms are distributed with the designated order depending on the recorded bit. However, there are non-negligible overlap between the levels in the tested configuration, caused by random disturbances like neighboring bit patterns and granular effects at the high track and linear densities. SER is measured as 0.3963 with a simple threshold scheme by the means of the centers of the histograms.

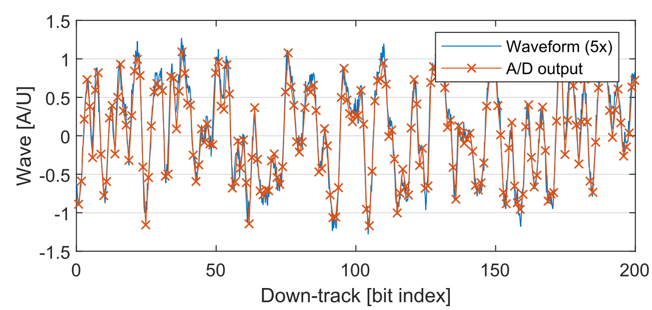

FIG. 2. Example of raw waveform and A/D samples of SR-DTR IMR.

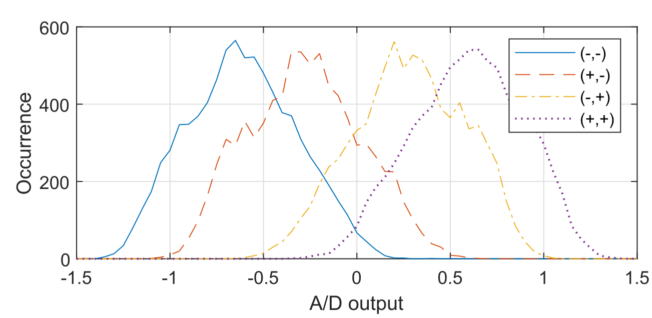

FIG. 3. Conditional distribution A/D samples of SR-DTR IMR.

In the SR-DTR IMR, one of the potential challenges is to record neighboring tracks synchronously, which may require extra efforts such as the write synchronization scheme[18] during writing, in order to mitigate the timing jitter as small as the media noise. In addition, track mis-registration during reading may also degrade the readback signals, for example, by shifting the center of 2nd and 3rd histograms toward their left and right respectively, when the reader moved toward the wide track. Therefore, off-track read capability should be investigated for SR-DTR IMR, and the following equalizer should be designed to suppress the potential degradation by track mis-registration, as well as other undesired interferences.

B. Joint-4L equalization and detection

For the 4L signal from the SR-DTR IMR, PR equalization is employed to control the residual interference in the equalized signal, which can be effectively used later for more reliable 4L Viterbi detection. For the PR target $\mathbf{q}$, the equalizer $\mathbf{h}$ can be obtained by the linear least square method as below,

$$\mathbf{h} = \arg\min_{\mathbf{h}'}\left(\hat{\mathbf{y}}^{4L} - \mathbf{h}' * \mathbf{x}^{4L}\right)^2, \tag{1}$$

where $\hat{\mathbf{y}}^{4L} = \mathbf{q} * \mathbf{z}^{4L}$, the target sequence with the PR targets, where $\mathbf{z}^{4L}$ is the 4L sequence of two tracks along the down-track direction, converted from $\mathbf{z}^{2b}$. The PR targets are aligned to the down-track direction. Due to the inevitable read offsets as discussed in Section II A, the PR target and equalizer may need to be customized adaptively by accounting the potential read-offset δ, and pairs of the PR target $\left\{\mathbf{q}^{(\delta)}\right\}$ and the equalizer $\left\{\mathbf{h}^{(\delta)}\right\}$ may need to be pre-computed through general PR target search for the given IMR configurations. For example, A/D sample $\mathbf{x}^{4L}$ with a read offset of 0.2 TP toward $2(i)+1$ track under the same configuration as the Fig. 2 is equalized with the PR target of [1, 0.2], and conditional histograms of A/D and equalizer outputs are plotted in Figs. 4(a) and 4(b), respectively. As shown in the plots, read offset causes undesired broadening and shift of conditional histograms of $\mathbf{x}^{4L}$, whereas the disturbance can be effectively compensated by the proposed 4L PR equalization. The PR equalizer reduces the equalization error by allowing intersymbol interference (ISI) along the down-track direction, while the controlled ISI for the given target can be used later for reliable detection.

To detect 2 bits or 4 levels of data per PR equalized sample, simple Viterbi detector is employed. The trellis has 16 states of the current and previous symbols, each having 4 levels, and each state has four incoming and outgoing branches. Euclidean distance from the equalized target is used for branch metric, which are accumulated as path metric along the trellis diagram. Trace-back depth is set to 5 for decision.

III. NUMERICAL EVALUATION

For numerical evaluation of the SR-DTR IMR, the MPM channel model[9] is employed, and BER performance of 4L equalization and detection is evaluated under various scenarios. The channel configurations are fixed as the typical IMR set up[9] with adjustments on the synchronized recording of neighboring tracks and the wide reader covering two adjacent tracks. The magnetic write width is set to 60 nm, so that the even and odd tracks are recorded with the same width along the cross-track direction, while the even tracks at the bottom show narrow footprint than the odd tracks. The magnetic read width is set to 72 nm to capture joint signal from two adjacent tracks together, of which response is obtained from the shielded three-dimensional model[19] with head electronic SNR of 30 dB. The magnetic media is modeled by 1.5 × 1.5 nm square micro-pixels, and mean grain diameter is set to 9 with standard deviation of 1.8 nm. Previously introduced Figs. 2 to 4 are intermediate signals from one

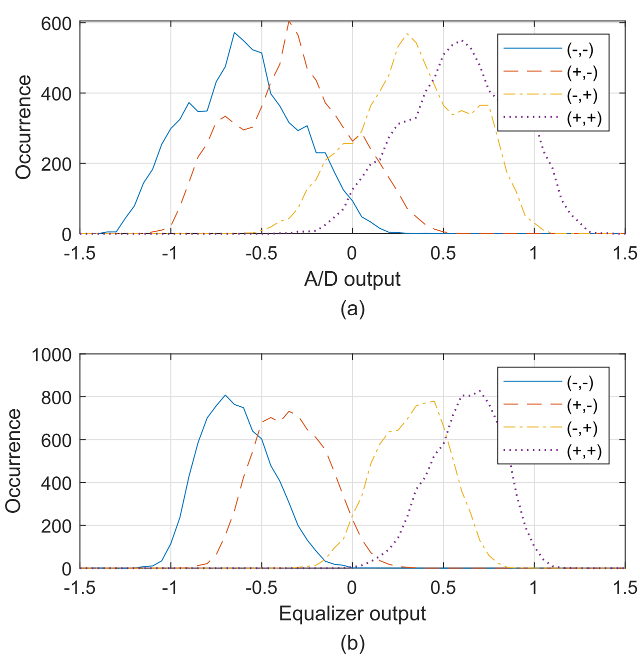

FIG. 4. Conditional distribution (a) A/D and (b) equalizer outputs of SR-DTR IMR with a read offset δ = + 0.2 TP with a PR target $\mathbf{q}$ = [1, 0.2].

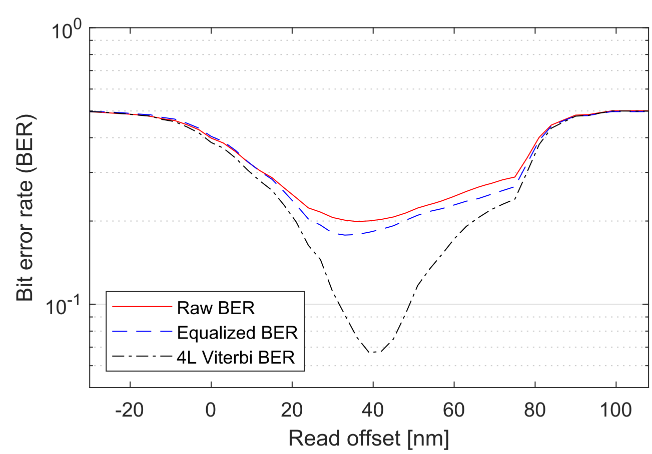

FIG. 5. BER bathtubs for SR-DTR IMR. Track density is set to 498 kTPI, with the linear density of tracks set to 1600 kBPI.

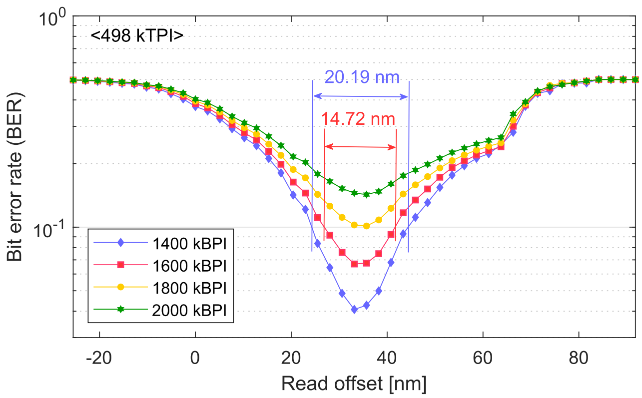

FIG. 6. BER bathtubs by joint-4L equalizer and Viterbi detector for the SR-DTR IMR. Linear densities are tested from 1400 kBPI to 2000 kBPI at 470 kTPI.

realization of the MPM channel simulations under 1600 kBPI and 498 kTPI scenario.

For the evaluation of the BER bathtubs of the SR-DTR IMR, bit sequences of nine tracks of 32kb lengths are generated in a pseudo-random manner, and recorded sequentially to the synthetic media in an interlaced order with designated kTPI and kBPI. Fig. 5 shows the BER profiles of the SR-DTR readbacks of the 5^{th} and 6^{th} tracks at 1600 kBPI and 498 kTPI. For performance comparison, the raw and equalized BER performances are evaluated by the simple thresholding. The blue dotted and black dotted lines are the BER bathtub of joint-4L equalizer without and with 4L detection respectively, which show improvements compared to that of the raw BER. As illustrated, the left slope and right slope in the BER profiles are different due to the im-balance of the residual footprints of two adjacent tracks. Besides, the BER profile is the combination of two individual track BER profiles. The inflection points appear around read-offset 80 nm in BER profiles are caused by the misalignment of the two BER profiles of individual tracks.

The BER bathtub curves of the SR-DTR IMR are evaluated for linear densities from 1400 to 2000 kBPI at fixed track density of

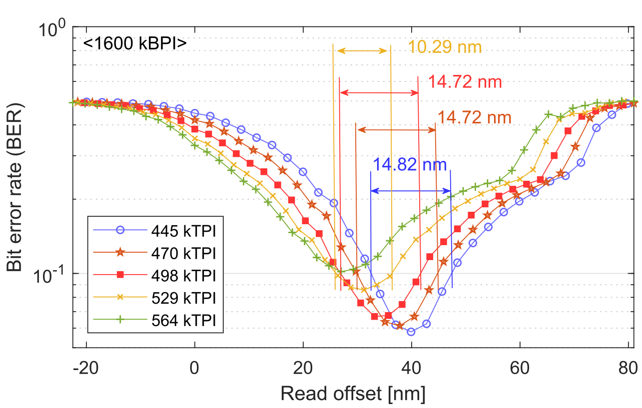

FIG. 7. BER bathtubs by joint-4L equalizer and Viterbi detector for SR-DTR IMR. Track densities are tested from 445 kTPI to 564 kTPI at 1600 kBPI.

498 kTPI as shown in Fig. 6. As the linear density decrease, the BER performance is more improved. In addition, the off-track capability (OTC) is also investigated, which denotes the bathtub width at the target BER order of 10^{-1} calculated using the linear interpolation. As illustrated, the OTC is appeared when the linear density is lower than 1800, which has 20 nm at 1400 kBPI.

Likewise, the BER performances of joint-4L equalizer with 4L detection are evaluated for the track densities from 445 kTPI to 564 kTPI at fixed kBPI of 1600 as shown in Fig. 7. As expected, the bathtubs can be broadened by relaxing the track density.

IV. CONCLUSION

This study shows the feasibility of 2X retrieval from IMR with the single reader dual-track readback (SR-DTR) approach. By employing a wide reader covering two adjacent tracks and imbalancing the residual footprints of the tracks by IMR, four level (4L) signal can be captured. By subsequent 4L PR equalization and detection, the dual-track data can be recovered simultaneously, enabling 2X readback with a single reader in magnetic recording disk drives. By customizing the write track widths of top and bottom tracks favorable for the 4L signal,[17] the SR-DTR IMR may achieve extra performance gain in ADC, while keeping the 2X retrieval capability. For more precise assessments of the SR-DTR IMR beyond this numerical simulation efforts, spin-stand tests may be needed to take into account practical degradations and disturbances including random cross-track offsets during recording and reading.

ACKNOWLEDGMENTS

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2017R1D1A1B03034987).

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