DATA RECOVERY FOR 3D MAGNETIC RECORDING

Kheong CHAN[1], Ahmed ABOUTALEB[2], Krishnamoorthy SIVAKUMAR[2], Benjamin BELZER[2], Roger WOOD[2], and Susanto RAHARDJA[3]

1) Nanjing Institute of Technology, Nanjing, China, kheongsann@ieee.org

2) Washington State Univ., Pullman, WA, USA, {ahmed.aboutaleb, belzer, siva}@wsu.edu, roger.wood@ieee.org

3) Northwestern Polytechnical University, Xian, China, susantorahardja@ieee.org

I. INTRODUCTION

Solid State Drives (SSD) compete with Hard Disk Drives (HDD) in the data storage market. Recent advances in SSD capacity/cost have come from arranging the flash memory cells not just on the 2D surface but from also stacking many cells vertically through the 3rd dimension. The same option has not been seen as a practical approach for HDD technology that is based on magnetic recording. Data can only be written to and read from just above the surface of the medium, and any data on additional layers deeper in the medium is profoundly affected by the additional spacing and loss of resolution. Nevertheless, modest gains may be still be possible. Earlier work suggested gains around 17% for two stacked layers [2]. That work only examined a single isolated track on each of two layers and just one reader. In this new work, we examine a minimal 3D configuration again comprising two layers, where two adjacent tracks on the upper layer straddle a double width track on the lower layer. We take the writing process as a given—for instance utilizing Microwave Assisted Magnetic Recording [1]. For readback, we variously assume 1, 2, or 3 readers arrayed above the data tracks.

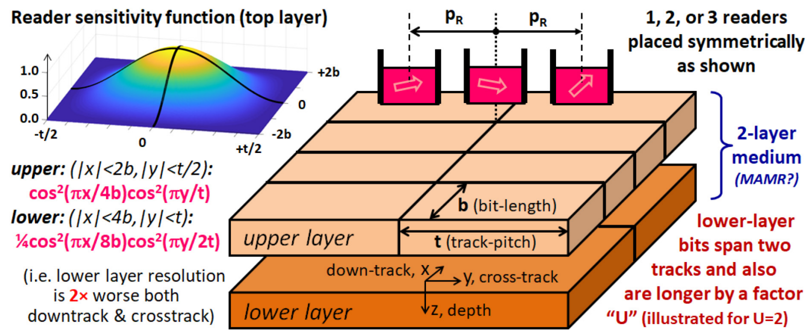

Fig. 1. The simple 3D magnetic recording configuration used for analysis.

Figure 1 illustrates the very simple 3D configuration that we examine. We assume the resolution on the lower layer is lower by a factor of two both down-track and cross-track. With this in mind, we propose data on the lower layer to be written with twice the track-width and with a bit length 'U' times longer than in the upper layer. This implies a maximum areal-density gain of $1+1/(2U)$. The read sensitivity function is taken to have a 2D cosine-squared form separable along the down-track and cross-track axes. The respective 50%-widths are $2b \times t/2$ on the upper layer and $4b \times t$ on the lower layer, where b and t are the bit-length and track-pitch on the upper layer. There are known levels of interference between these three data streams plus interference from unknown data outside the wanted tracks. The noise contributions in the reference configuration (upper layer alone) are a nominal 1/3 from the reader and 2/3 from the medium. The introduction of the lower layer then adds another $1/(6U)$ to the total noise. Note: this differs from the $1/(3U^2)$ factor in [2] because of the change to 3D and to be more consistent with measured noise vs. density. The lower layer has one quarter the noise-power (half the resolution on both axes) of the upper layer and the media noise is further reduced with U due to there being fewer transitions. The sensitivity function is assumed to include the response to the write process and any channel equalization. For simplicity, the down-track noise is assumed to be equalized to be white, a necessity for the maximum likelihood detector. The bit-streams, $\boldsymbol{a}_1$, $\boldsymbol{a}_{2,L}$, $\boldsymbol{a}_{2,R}$ are written on the lower layer and on the left and right tracks on the upper layer, respectively. The readback signal for a reader in a given cross-track position, $y = p$, is now given by ('*' denotes a down-track convolution)

$$\boldsymbol{r}(p) = \boldsymbol{n}_{reader}(p) + [c_{2,LL}(p)\boldsymbol{a}_{2,LL} + c_{2,L}(p)\boldsymbol{a}_{2,L} + c_{2,R}(p)\boldsymbol{a}_{2,R} + c_{2,RR}(p)\boldsymbol{a}_{2,RR}] * \boldsymbol{h}_2 + \boldsymbol{n}_2(p)$$
$$+ [c_{1,LL}(p)\boldsymbol{a}_{1,LL} + c_1(p)\boldsymbol{a}_1 + c_{1,RR}(p)\boldsymbol{a}_{1,RR}] * \boldsymbol{h}_1 + \boldsymbol{n}_1(p).$$

Outside the three wanted tracks are four unwanted tracks $\boldsymbol{a}_{2,\mathrm{LL}}, \boldsymbol{a}_{2,\mathrm{RR}}$ to the left and right on the top layer and, similarly, $\boldsymbol{a}_{1,\mathrm{LL}}, \boldsymbol{a}_{1,\mathrm{RR}}$ on the bottom layer. These may generate additional unknown inter-track interference (ITI) depending on the positions, p, of the readers. The coefficients, $c(p)$, are the position-dependent weightings for each contributing bit-stream. They are calculated as the fraction of the reader-response that falls over the assumed rectangular cross-track profile of the written tracks. The down-track behavior is captured in the discrete-time responses, $\boldsymbol{h}_2 = [0.5, 1, 0.5]$ and $\boldsymbol{h}_1 = [0.0732, 0.25, 0.4268, 0.5, 0.4268, 0.25, 0.0732]$ (see Fig. 1). In

Kheong Sann CHAN
kheongsann@ieee.org
+86-25-8611-8121

addition, the total read signal includes three sources of white Gaussian noise $\boldsymbol{n}_{reader}, \boldsymbol{n}_2, \boldsymbol{n}_1$ due to reader thermal noise, top-layer and bottom-layer media noise, respectively. These three noise sources as seen by a given reader are independent of each other. However, media noise between two readers in different positions, p, is correlated to the extent their sensitivity functions overlap as the readers are picking up media noise from the same grains in their overlapping region.

II. RESULTS AND DISCUSSION

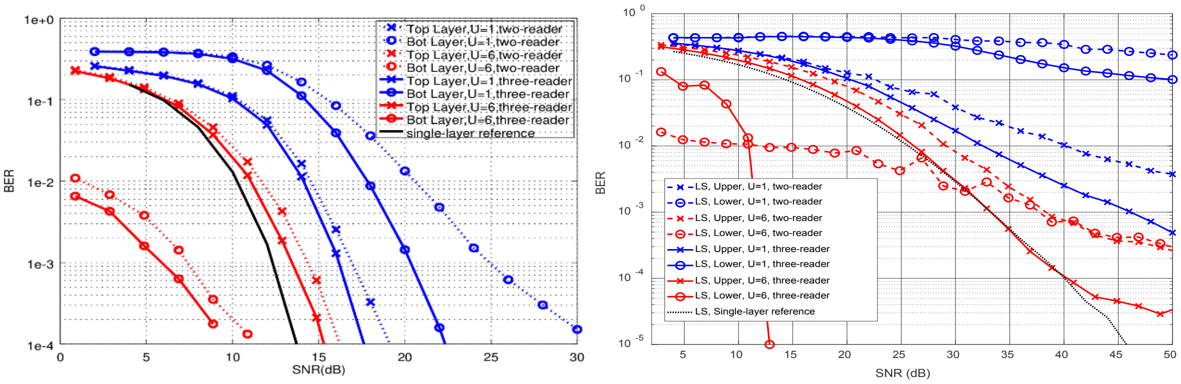

Fig. 2. BER vs. SNR performance of the proposed Viterbi (left) and LS threshold (right) detectors with 2 and 3 readers. Data density on the lower track is either full density ($U = 1$) or one-sixth density ($U = 6$).

We demonstrate simulation results for the two proposed approaches for detection of bit sequences over the 3D magnetic recording system: a Viterbi detector and a least-squares (LS) threshold detector. The readers are assumed to be located at $y = -0.5t, 0, 0.5t$. After passing through a matrix to de-correlate the noise between readers, the joint Viterbi detector estimates the two bit sequences on the upper layer and one on the lower layer. A state in the Viterbi trellis consists of 2 bits from the upper-left layer, 6 bits from the lower layer and another 2 bits from the upper right layer, or 10 bits, giving 1024 states in total. The branch metric is the sum of the individual mean squared errors between the readback and the expected output for each reader. For the LS detector, by defining the column vectors of bit sequences and readings as $\mathbf{A} \triangleq \mathrm{col}[\boldsymbol{a}_{2,L}, \boldsymbol{a}_{2,R}, \boldsymbol{a}_1, \boldsymbol{a}_{bL,\mathrm{ITI}}, \boldsymbol{a}_{bR,\mathrm{ITI}}]$ and $\mathbf{R} \triangleq \mathrm{col}[\boldsymbol{r}_L, \boldsymbol{r}_C, \boldsymbol{r}_R]$ (three readers) or $\mathbf{R} \triangleq \mathrm{col}[\boldsymbol{r}_L, \boldsymbol{r}_R]$ (two readers), respectively, we can write $\mathbf{R}$ as $\mathbf{R} = \mathbf{HA} + \mathbf{Z}$, where $\mathbf{H}$ accounts for the convolution relation between the masks and the bit sequences as well as the superposition of the contributions from each layer to the readings, and $\mathbf{Z}$ is the effective additive noise with the covariance $\mathbf{C}_\mathbf{Z}$. A least-squares (LS) threshold detector can be obtained using $\widehat{\mathbf{A}} = \mathrm{sgn}[\mathbf{H}^\dagger\mathbf{R}]$, where $\mathbf{H}^\dagger = (\mathbf{H}^T\mathbf{C}_\mathbf{z}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{C}_\mathbf{z}^{-1}$ is the pseudo-inverse matrix (computed offline). Hence, the real-time implementation complexity of the LS detector is $5N$ scalar multiplications and $5N - 1$ scalar additions per data bit. Since error rates can differ widely between the two layers, depending on U, we added an iterative step—subtracting the effect of the more reliable bit estimates from the readings and re-estimating the less reliable bit sequence using the appropriate pseudo-inverse.

Figure 2 compares the bit error rate (BER) versus signal-to-noise ratio (SNR) performance of the Viterbi and LS threshold detectors for two- and three-reader configurations and for $U \in \{1, 6\}$, where the SNR is defined as the upper layer's signal power divided by the power of the upper-layer noise plus reader noise (excluding the lower layer). The performance of both detectors for a standard single-layer recording configuration is also included for reference. In the three-reader case with $U = 1$, the Viterbi detector achieves a BER of 10^{-2} by 14 dB and 18 dB on the upper and lower layers, respectively. However, the LS detector requires 32 dB SNR for the same performance on the upper layer and is not able to achieve this performance on the lower layer. The lack of a third reader increases the BERs on the lower layer more than on the upper layer. However, for $U = 6$, the BERs for both the Viterbi and LS detectors become more resilient to the lack of a third reader. This suggests a trade-off between adding a third reader and U that can be used in the design of 3D magnetic recording systems.

REFERENCES

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Kheong Sann CHAN
kheongsann@ieee.org
+86-25-8611-8121