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Review of Error Correction in 2D Shingled Magnetic Detection

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Abstract: This paper presents the review of error correction in 2D shingled magnetic detection. Shingled magnetic recording is one of the techniques proposed in literature for increasing the storage density of magnetic hard disk drive (HDD) due to the number of overwhelming advantages of shingled writing. The success of this technique lies with a proper signal processing and data update approach. In this paper, shingled magnetic recording and two-dimensional magnetic recording has been studied and the current researches done in the two areas has been reviewed with emphasis on elimination of inter-track-interference and inter-symbol-interference. In the reviewed articles studied, a summary was provided on each article depicting the technique adopted and the performance metrics of each of the articles. Summary was provided at the end of the article on the techniques reviewed based on the existing body of knowledge.

Keywords: Shingle magnetic detection, shingled writing, magnetic hard disk, shingled magnetic recording, two-dimensional magnetic recording

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1. INTRODUCTION

The hard disk drive (HDD) is an electromechanical data storage system that stores and retrieves digital data using magnetic storage. HDDs play a critical role in making access to information more affordable, realizable, and portable. Magnetic HDDs are the most popular storage medium in millions of personal computers used in offices, families, and businesses. They act as the basis for all internet and intranet communications. Figure 1 presents a magnetic HDD [1].

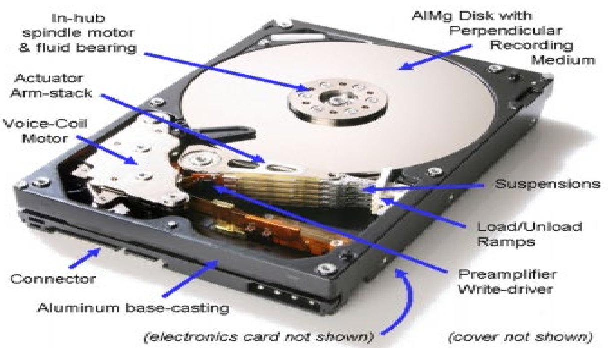

Figure 1. Magnetic Hard Disk Drive [1]

Since IBM introduced the first magnetic HDD in 1956, the storage capacity of magnetic HDDs has increased exponentially, amounting to around six (6) figures, with an average annual increase of greater than 30% in the number of bits/in^2. However, due to the magnetic recording medium's superparamagnetic limit (1 Tb/in^2), this annual rise in areal density has come to a halt [2,3].
The growth curve of areal-density is presented in Figure 2.

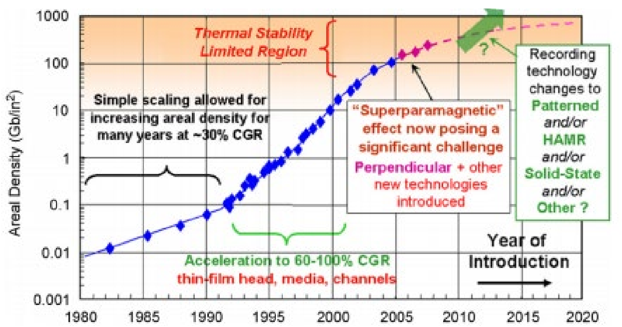

Figure 2. Growth of Areal Densities for Conventional Recording [1]

The superparamagnetic limit is a trade-off between the media trilemma's: signal-to-noise ratio (SNR), writability, and thermal stability as shown in Figure 3 [4].

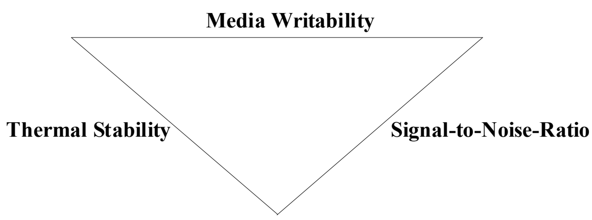

Figure 3: Media Trilemma [4]

As bit sizes shrink, one or more of the three (3) competing parameters often gives way. As a result, the competing parameters should be forced to their limits in order to increase the life span of the magnetic recording [4] Different novel architectures have been proposed in literature to keep the trend of superparamagnetic limit increasing, among which the common approaches for the expansion of the magnetic HDD include Bit Patterned Magnetic Recording (BPMR), which tries to address the problem of signal to noise ratio of the media trilemma by isolating bit positions as far as possible from each other, Energy Assisted Magnetic Recording (EAMR), which involves assisting the head either by locally heating the bit or by adding a radio frequency magnetic field to write on higher anisotropy media, that enables thermal stability of small grains. EAMR is broken down into Heat Assisted Magnetic Recording (HAMR) and Microwave Assisted Magnetic Recording (MAMR). Shingled Magnetic Recording (SMR), tries to address the stability and writability problem without drastic change in the current media technology. It is complemented with Two-Dimensional Magnetic Recording (TDMR), which approaches the trilemma from the perspective of SNR and signal processing [5].

The SMR is a technique used for increasing the areal data density in HDDs. It is based on overlapping written data so as to eliminate the write head limitation of bit size and make the tracks as small as possible. It tries to address the stability and writability problem without drastic change in the current media technology. The success of this technique lies with a proper signal processing and data update approach [6]. However, the problems of inter-symbol interference (ISI) along the tracks and inter-track interference (ITI) exist in SMR as the tracks are packed very closely. Thus, for an adequately performing SMR disk, these issues become very vital and has to be dealt with [7]. Despite the drawbacks of SMR, it becomes more popular technology that will keep tracking the expansion capacity of magnetic media in the immediate future. Figure 4 presents the writing process in shingled magnetic recording.

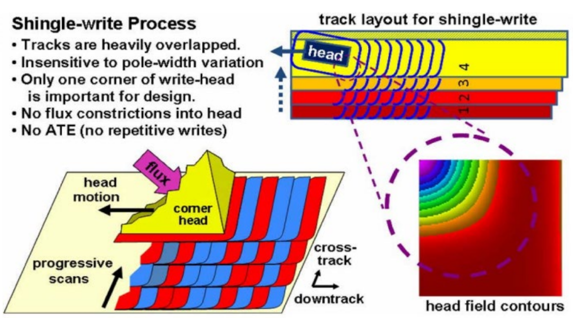

Figure 4. Writing Process in Shingled Magnetic Recording [6]

TDMR is a magnetic recording architecture developed by [6] for areal densities towards 10TB/in^2 as the traditional means cannot go beyond 1Tb/in^2. It approaches the trilemma from the perspective of SNR and signal processing. The channel bit cell of the media is shrunk without reducing the grain-size proportionately, which causes the SNR to go below the levels needed by conventional 1D recording systems. The main challenges of TDMR include: coding and signal processing complexities [4].

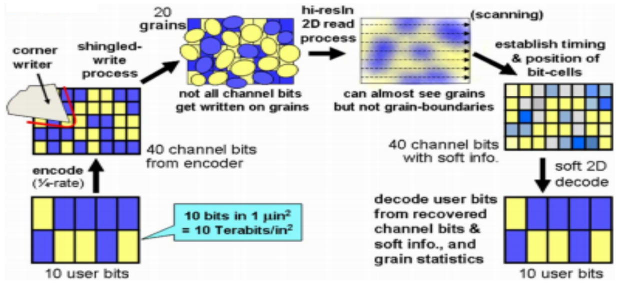

Figure 5. Two-Dimensional Magnetic Recording (TDMR) [2]

The TDMR system uses shingled write recording for data writing and two-dimensional signal processing techniques for data recovery. Amongst the 2D signal processing techniques is 2D detection used to detect 2D interferences, which is a fundamental component in TDMR systems, optical storage systems and wireless communications [4].

The 2D detector is applied for joint track detection that completely utilizes inferences from both along track and across track directions. This improves system performance and makes detection process more reliable.
In literature, various 2D detection techniques have been developed, each of which corresponds to a different trade-off between detection performance and computational complexity. These techniques include the use of a full 2D Soft Output Viterbi algorithm (SOVA) or linear equalizer to eliminate interference in one direction and partial response maximum likelihood detection in the other direction [8]. Full 2D SOVA, on the other hand, has a high level of complexity but produces excellent results. While using a linear equalizer reduces the complexity of the detector, it has a performance loss under ISI and ITI conditions [9]. The rest of the paper is organized as follows; section I gives the basic introduction of error correction in 2D shingle magnetic detection scheme, and section II elaborates on past works done in the field of shingle magnetic detection, and also a summary of the various detection and equalizations done by other researchers. Finally, section III gives the conclusion.

2. RESEARCHES ON SHINGLED MAGNETIC RECORDING

This section presents the review of works done in the area of shingled magnetic recording and two-dimensional magnetic recording using different types of detection and equalization techniques.

[10] proposed a serial concatenation of 2D-SOVA and regular Viterbi algorithm (VA) for 2D detection and equalization of SMR media. The 2D SOVA along tracks and Viterbi across tracks were implemented to respectively remove the effect of ISI and ITI. The system performance

was compared when the 2D-SOVA across-track was implemented for removing ITI while using the 1D Viterbi detector to remove ISI along the track. The results show better performance by the system that used 2D-SOVA across the track, as against using it along the track. In this research, the authors used only detectors without taking advantage of error correction codes which can help in improving performance. The performance of the detector used was excellent as compared to the use of the 1D maximum likelihood (ML) detector.

[11] presented a TDMR as a method of going beyond 1Tbit/in^2 areal-density while retaining relatively conventional magnetic components. Firstly, TDMR was introduced and modest gains were provided without undue complexity. Waveforms capture from the same reader at several off-track positions, radii, and track pitches were combined to assess the dual reader gains.

[12] examined shingled writing process, signal processing, and detection techniques for readback waveforms. The readback waveforms were studied in terms of signal features, noise behavior, and IT in both 1D and 2D. Also, the performance of different detection and equalization techniques were compared and the result showed that 2D magnetic recording has a density gain of about 10% as that of the conventional single-track recording. It is confirmed that the gains depend on reader position, reader width, and number of read heads while the performance of TDMR depends on how advanced is the signal processing technique. These techniques mostly involve maximum likelihood detection techniques that check every possible sequence of bits or every individual bit to determine the most likely saved data.

[13] presented a granular model tiling, capable of reading and writing process in TDMR. Generalized belief propagation was utilized to generate a marginal posterior probability for graph factor assembling. The result showed a vast improvement in detection while the modulation codes improve the general performance of the TDMR system. Detection and decoding schemes, decryption, and demodulation performed better as compared to concatenated schemes.

[14] presented magnetic read widths optimization in TDMR for micromagnetic simulation. The reader positions and magnetic read widths optimization in TDMR were explored to optimize areal density gain against SMR. 511-bit maximal-length micromagnetic waveforms were optimized to the pseudorandom binary sequence. The magnetic read widths for two readers were considered and the optimal reader offset that gives the largest areal density gain recorded. For areal density gain enhancement, the magnetic read widths for the two readers were varied and the effort of TDMR areal density gain was identified using software channel.

[15] presented a strategy that includes the utilization of multi-level 2D Bahl Cocke Jelinek and Reviv (BCJR) detector and regular BCJR detector for the elimination of ISI along-track and ITI across tracks respectively. This is to perform joint track detection. The results showed that the developed scheme has less complexity than that of full joint-track detection. However, the work presented the use of 2D-BCJR along-track without applying it across-track which was shown to have inferior performance. It also used no error correction in the system.

[9] studied a BCJR detector for extracting data from a TDMR system by combining 2D multi-level and regular BCJR detectors using the SMR media. The 2D multi-level BCJR detector was used to cancel ISI along the track while the regular BCJR detector was used to cancel ITI across the track. The C programming environment was used for the development and implementation of the simulation model. It was assumed that the data recorded on the media was written in sectors containing 8 tracks and 4096 bits per sector. The channel (SMR) was considered to contain ITI of two tracks, while jitter noise power and additive white gaussian noise power were set to respectively constitute 80% and 20% of the total signal noise power. Linear equalizer (size 12) with 0.4, 1.0, 1.0, 0.4 as the target was employed to shape the received data along the track's direction. Computational cost and latency involved in processing each symbol were used to evaluate the cost overhead of implementation of the multi-level 2D BCJR detector.

[16] studied a multi-input single-output TDMR gain in a magnetic tape system. The multi-input single-output TDMR was developed by first acquiring data using conventional and tape media. The detector's SNR across-track profile was then used to evaluate the processed signal by employing a 2D read-back signal generated from the waveform using a conventional single reader tape head. Simulation results showed that based on the selected reader pitch, the 2-D equalization was achieved by either a significant gain of 215% increase in tracking margin as that of the conventional 1D signal processing scheme or an extra SNR gain with an approximately 30% reasonable increase in tracking margin.

[17] proposed a redundancy array of independent disks (RAID) as an innovation that used SMR disk when building a basic RAID for arrangement and improved its performance when compared with the basic one, called (RAID 4SMR). The first practical solution used for managing a long-structure of limited metadata storage capacity was offered by the RAID scheme. This explores a spectrum to design a parameter for shingle write disks (SWD) like object base stores or file system base to address the new behavior of the disk. The result shows that standard RAID allows adaptation of SMR disks when RAID 4SMR compared with the garbage collection up to 56%, and it reduces the penalty performance. Previous approaches were based on RAID 5, while the one presented in this article is based on RAID 4.

[18] presented a limited area impact probabilistic detector, referred to as the local areas influences probabilistic (LAIP) detector, for approximating the interactions of magnetic grain (MG) with coded data bits in 2D MR. This was joined with a 2D BCJR based detector for eliminating ITI and ISI. In addressing the interactions of grain-bit, the LAIP detector in this research was considered as dynamic grain state estimation. The LAIP detector was designed to manage read-head data caused by the grain-flipping probability model. The LAIP detector sends an estimate of the log-likelihood ratio of coded bits and convolution mask of local ISI or ITI to the BCJR-based detector. It was suggested that the performance of the LAIP detector can be enhanced in the future by increasing the memory storage resources. The results showed that the developed detector obtains a BER reduction of 11.3% as compared to a two-dimensional

linear equalizer-based system accompanied by a 2-track BCJR detector with 2D pattern-dependent noise prediction.

[19] presented a low complexity 2D method for multi-track 2D TDMR channel with SMR media. The method made used of serially concatenated 2D maximum a posteriori (MAP) with a regular MAP detector for multi-track joint detection of the 2D signal. The 2D MAP detector was applied along-track direction in order to cancel ISI, while the regular MAP detector was used across-tracks to cancel ITI. Simulation results showed that the serially concatenated 2D MAP with regular MAP detector outperformed full 2D detector in terms of complexity for a joint signal detector on an 8-track SMR media.

[20] presented a two different coding approaches of concatenated single parity codes, which involved both along and across track in TDMR media. Along the track technique made use of two concatenated single parity bit codes along the track direction which was separated by a dithered relative prime (DPR) interleaver. However, the across track technique uses two single parity bits codes in both across and along track directions without an interleaver. Simulations were carried out, and it showed that along track technique had a better performance in terms of ISI and ITI when applied to a TDMR. The authors suggested that an improved technique which is less complex and more powerful could be adopted other than adopting the DPR interleaver alone.

From the reviewed literatures, it is evident that magnetic recording has received research attention leading to development of different 1D and 2D detection and equalization techniques on shingled magnetic recording and two-dimensional magnetic recording. Table I presents the summary of what was done, the detection schemes and the performance metrics used for their evaluations.

Table 1. Summary of Works

S/N	Authors	What was done	Scheme	Performance Metrics
1	[10]	Concatenated 2D SOVA for two dimensional maximum likelihood detection	Soft Output Viterbi Algorithm (SOVA) and a Viterbi detector	Computational complexity
2	[11]	2-D magnetic recording: Progress and evolution	A stacked two-element reader operating on shingled magnetic recording tracks and a two-input equalizer feeding a standard data detector.	Off-track positions, radii, and track pitches
3	[12]	A study of TDMR signal processing opportunities based on quasi-micromagnetic simulations	Maximum likelihood detection techniques	Density gains
4	[13]	Read Channel Modeling, Detection, Capacity Estimation and Two-Dimensional Modulation Codes for TDMR	Generalized Belief Propagation (GBP) based 2D detection scheme	Detection of the grain states
5	[14]	Optimization of magnetic read widths in two-dimensional magnetic recording based on micromagnetic simulations	The optimization is based on waveforms from 511-bit maximal-length pseudo-random binary sequence (PRBS) patterns.	Areal density gain
6	[15]	Approximate expressions for the magnetic potential and fields of 2-D, asymmetrical magnetic recording heads	Scalar magnetic potential and 2-D asymmetrical magnetic heads and their Fourier transforms	Computational complexity
7	[9]	2D BCJR along track and across tracks detection for shingled magnetic recording media	A multi-level 2D BCJR detector along-track for ISI cancellation and regular BCJR detector across tracks for ITI cancellation.	Computational cost and latency
8	[7]	Performance of 2D SOVA Along and Across Track in SMR Media	A 2D SOVA along the tracks to eliminate the effect of ISI and Viterbi detector across the tracks to remove ITI. The second uses 2D-SOVA across the tracks and VA along the tracks.	Computational complexity

9	[16]	A Study of Two Dimensional Magnetic Recording for Magnetic Tape Systems	The MISO-TDMR gain in a magnetic tape system was studied under the condition where the bit aspect ratio is 22%–37% compared with that of the current tape system.	Detector- SNR cross-track profile
10	[17]	RAID Array with SMR Disk for Mass Storage Systems	A novel use of SMR disks with redundant array of independent disks arrays, specifically building upon and compared with a basic RAID 4 arrangement.	Garbage collection and penalty performance
11	[18]	ISI/ITI turbo equalizer for TDMR using trained local area influence probabilistic model	A LAIP detector for estimating magnetic grain interactions with coded data bits in two-dimensional magnetic recording is combined with a 2D BCJR-based detector for joint removal of ITI and ISI	BER reduction
12	[19]	2D method for multi-track 2D TDMR channel with SMR media	A technique which used serially concatenated 2D MAP with a regular MAP detector for multi-track joint detection of the 2D signal.	Complexity reduction
13	[20]	Two different coding approaches of concatenated single parity codes which included along and across track in a TDMR media	Along track technique uses two concatenated single parity bits codes along the track which was separated with a DPR interleaver, while across technique used two single parity bits codes across and along the track without an interleaver	Reduced ISI and ITI performances

3. CONCLUSION

The paper has reviewed the prospects of expanding the areal density of magnetic recording of hard disk drive beyond 1Tb/in^2 using shingled magnetic recording and two-dimensional magnetic recording. Various detection techniques such as Soft Output Viterbi Algorithm (SOVA), 2D-SOVA, Viterbi detector, 2D BCJR detector, multi-level 2D BCJR detector, local area influence probabilistic (LAIP) detector and Maximum likelihood detection techniques amongst other detectors has been used for the effective removal of ITI and ISI along or across the tracks of shingled media at different degrees of performance. The performance of the detectors has been evaluated using garbage collection, penalty, BER reduction, computational complexity, computational cost, areal density gain and latency, etc.

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REFERENCES

[1] Wood, R. Future Hard Disk Drive Systems. *J Magn Magn Mater* **2009**, *321*, 555–561.

[2] 2. Wood, R. The Feasibility of Magnetic Recording at 1 Terabit per Square Inch. *IEEE Trans Magn* **2000**, *36*, 36–42.

[3] 3. Albrecht, T.R.; Arora, H.; Ayanoor-Vitikkate, V.; Beaujour, J.-M.; Bedau, D.; Berman, D.; Bogdanov, A.L.; Chapuis, Y.-A.; Cushen, J.; Dobisz, E.E. Bit-Patterned Magnetic Recording: Theory, Media Fabrication, and Recording Performance. *IEEE Trans Magn* **2015**, *51*, 1–42.

[4] 4. Chan, K.S.; Radhakrishnan, R.; Eason, K.; Elidrissi, M.R.; Miles, J.J.; Vasic, B.; Krishnan, A.R. Channel Models and Detectors for Two-Dimensional Magnetic Recording. *IEEE Trans Magn* **2010**, *46*, 804–811.

[5] 5. Shiroishi, Y.; Fukuda, K.; Tagawa, I.; Iwasaki, H.; Takenoiri, S.; Tanaka, H.; Mutoh, H.; Yoshikawa, N. Future Options for HDD Storage. *IEEE Trans Magn* **2009**, *45*, 3816–3822.

[6] 6. Wood, R.; Williams, M.; Kavcic, A.; Miles, J. The Feasibility of Magnetic Recording at 10 Terabits per Square Inch on Conventional Media. *IEEE Trans Magn* **2009**, *45*, 917–923.

[7] 7. Abdulrazaq, M.B.; Ahmed, M.Z.; Davey, P. Performance of 2D SOVA along and across Track in Shingled Magnetic Recording Media. *Telfor Journal* **2017**, *9*, 38–42.

[8] 8. Zheng, N.; Venkataraman, K.S.; Kavcic, A.; Zhang, T. A Study of Multitrack Joint 2-D Signal Detection Performance and Implementation Cost for Shingled Magnetic Recording. *IEEE Trans Magn* **2014**, *50*, 1–6.

[9] Almustapha, M.D.; Ahmed, M.Z.; Ambroze, M.A.; Abdulrazaq, M.B. 2D BCJR along Track and across Tracks Detection for Shingled Magnetic Recording Media. In Proceedings of the 2017 40th International Conference on Telecommunications and Signal Processing (TSP); IEEE, 2017; pp. 515–519.

[10] Muhammad, B.A.; Mohammed, Z.A.; Paul, D. Concatenated 2D SOVA for Two Dimensional Maximum Likelihood Detection. In Proceedings of the 2015 23rd Telecommunications Forum Telfor (TELFOR); IEEE, 2015; pp. 441–444.

[11] Wood, R.; Galbraith, R.; Coker, J. 2-D Magnetic Recording: Progress and Evolution. *IEEE Trans Magn* **2015**, *51*, 1–7.

[12] Vasić, B.; Khatami, M.; Nakamura, Y.; Okamoto, Y.; Kanai, Y.; Barry, J.R.; McLaughlin, S.W.; Sadeghian, E.B. A Study of TDMR Signal Processing Opportunities Based on Quasi-Micromagnetic Simulations. *IEEE Trans Magn* **2015**, *51*, 1–7.

[13] Khatami, S. Read Channel Modeling, Detection, Capacity Estimation and Two-Dimensional Modulation Codes for TDMR. **2015**.

[14] Park, J.; Lengsfield, B.; Galbraith, R.; Wood, R.; Fu, S. Optimization of Magnetic Read Widths in Two-Dimensional Magnetic Recording Based on Micromagnetic Simulations. *IEEE Trans Magn* **2015**, *51*, 1–4.

[15] Aziz, M.M.; Edress, A.I.; Wright, C.D. Approximate Expressions for the Magnetic Potential and Fields of 2-D, Asymmetrical Magnetic Recording Heads. *IEEE Trans Magn* **2015**, *52*, 1–12.

[16] Musha, A. A Study of TDMR for Magnetic Tape Systems. *IEEE Trans Magn* **2018**, *55*, 1–5.

[17] Le, Q.; Amer, A.; Holliday, J. RAID 4SMR: RAID Array with Shingled Magnetic Recording Disk for Mass Storage Systems. *J Comput Sci Technol* **2019**, *34*, 854–868.

[18] Sun, X.; Shen, J.; Belzer, B.J.; Sivakumar, K.; James, A.; Chan, K.S.; Wood, R. ISI/ITI Turbo Equalizer for TDMR Using Trained Local Area Influence Probabilistic Model. *IEEE Trans Magn* **2019**, *55*, 1–15.

[19] Almustapha, M.D.; Kabir, M.T.; Abdulkarim, H. Performance of Concatenated 2D MAP for Multi-Track Signal Detection. *Nigerian Journal of Engineering* **2022**, *29*, 85.

[20] Almustapha, M.D.; Abdulkarim, H.; Musa, I.K.; Salisu, S. Performance of Concatenated Single Parity Bit Coding Along and Across Track in TDMR Media. *Nigerian Journal of Engineering* **2022**, *29*, 46.