Pushing the Limits of Areal Density: Fusing Advanced Channel Coding, HAMR, and SMR in Next-Generation HDDs

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Pushing HDD areal density to new extremes requires a fusion of cutting-edge technologies. This paper examines the interplay of advanced coding strategies, Heat-Assisted Magnetic Recording (HAMR), and Shingled Magnetic Recording (SMR), and how their integration enables substantial gains in areal density. We present a series of measured results demonstrating how jointly-optimized modulation and LDPC coding enhances performance across ePMR, HAMR, and SMR environments. Through these demonstrations, we showcase the tangible gains enabled by these technologies and outline a clear trajectory for continued areal density scaling in next-generation HDDs.

***Index Terms*— channel coding, hard disk drives, heat assisted magnetic recording, shingled magnetic recording**

I. Introduction

The relentless demand for higher storage capacity in hard disk drives (HDDs) necessitates aggressive advancements in areal density. Achieving significant gains from today's baseline requires more than incremental progress—it calls for a fusion of transformative technologies. Over the past decade, the channel coding strategies implemented in nearly all commercial HDDs have remained largely unchanged. Meanwhile, the recording physics—including ongoing use of energy-assisted Perpendicular Magnetic Recording (ePMR), as well as the emergence of Heat-Assisted Magnetic Recording (HAMR) and the increasing adoption of Shingled Magnetic Recording (SMR)—has shifted dramatically. These shifts demand a fundamental rethinking of channel coding design.

This paper presents a systematic exploration of three interdependent innovations: advanced coding strategies, HAMR, and SMR. We demonstrate how each contributes individually to areal density improvements, and more critically, how their interaction lays the foundation for a radical leap in HDD capabilities. Our combined analysis of these technologies outlines a clear path forward—one in which coordinated innovation across the full stack of read/write technologies is essential for enabling the next generation of ultra-high-density HDDs.

II. Modulation-aware coding for high-density recording

Channel coding is foundational to pushing areal density, especially as track pitch narrows and noise increases. In this section, we introduce a refined coding architecture that enhances both the modulation and Low-Density Parity-Check (LDPC) components, enabling deeper channel optimization.

One of the most persistent challenges in magnetic recording is the presence of consecutive transitions—closely spaced flux reversals—which generate particularly noisy and poorly resolved readback signals. Maximum Transition Run (MTR) codes address this by explicitly prohibiting transition runs beyond a chosen threshold (e.g., J=3), and continue to be effective in scenarios where full elimination of these high-risk patterns is achievable without excessive rate loss.

Rather than outright forbidding specific patterns or 'contexts', Mutual Information (MI) is used to shape the code toward less harmful patterns, reducing the occurrence of low-MI patterns while preserving a higher overall code rate. These codes-often implemented via constrained Markov models or arithmetic encoders-achieve a careful trade-off between pattern suppression and code rate. Figure 1 shows the MI across all 5-bit contexts for three modulation strategies: an unconstrained (uniform) code, a classic MTR (J=3) constrained code, and an MI-optimized code.

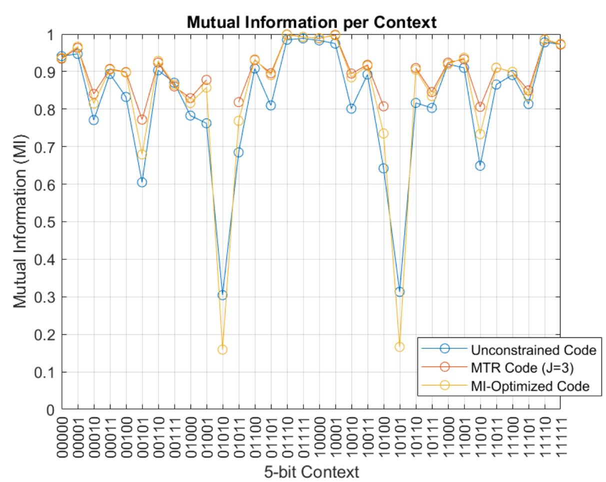

Fig. 1. Mutual information per 5-bit context for three modulation codes: Unmodulated, MTR (J=3), and MI-Optimized.

Layered on top, LDPC codes are re-optimized to account for these reshaped modulation statistics. Mutual information, a proxy for iterative decoder success, guides joint LDPC and modulation optimization [1]. Figure 2 illustrates a MI-based areal density contour. This surface serves as a map for identifying the modulation-LDPC pair that maximizes areal density for a given head/media/radius combination. The peak of the contour reflects the optimal pairing of modulation shaping and code rate, underscoring the need to co-design both elements as a function of channel conditions.

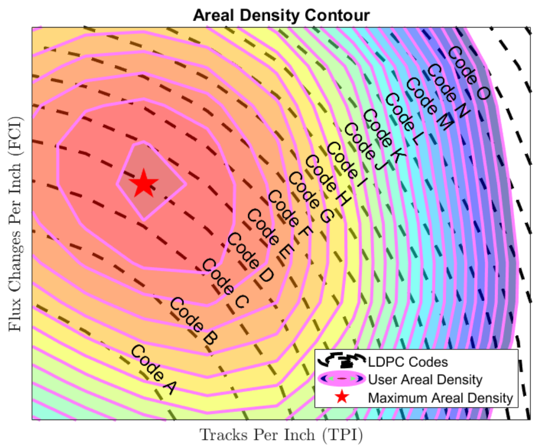

Fig. 2. Areal density contour based on mutual information. Color shows achievable density; dashed lines indicate optimized LDPC codes. Peak is found via joint modulation–LDPC optimization.

III. HAMR-DRIVEN TRACK PITCH REDUCTION AND CODING SYNERGY

HAMR enables narrower track pitch by focusing a tightly confined thermal spot on the media during writing, temporarily lowering the coercivity of high-anisotropy grains. This smaller thermal spot and sharper thermal edge gradient enable more precise magnetization switching without requiring increased write current and reduce adjacent track interference.

However, laser power must be carefully managed. While higher laser current can enhance signal quality and support higher linear densities, it also accelerates component wear. Operating at lower laser power improves reliability and extends lifetime — but also degrades SNR and increases jitter.

While HAMR alone provides areal density gains over ePMR, further improvement is enabled when the modulation and LDPC codes are optimized for the degraded channel conditions at reduced laser power. Figure 3 shows the areal density gain versus laser current. While the optimal Bits Per Inch (BPI) may decrease slightly at these lower laser powers, the associated Tracks Per Inch (TPI) gains more than compensate, yielding a net increase in areal density. This further lowers the Bit Aspect Ratio (BAR), enabling density scaling beyond ePMR.

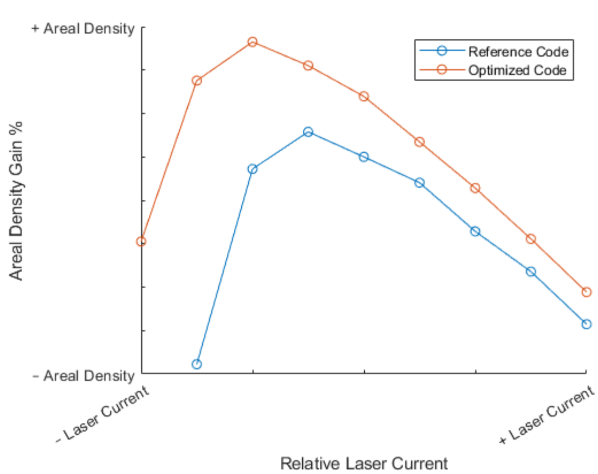

Fig. 3. Areal density and lifetime improvements via laser current reduction

IV. SHINGLED MAGNETIC RECORDING IN HIGH-TPI REGIMES

Shingled Magnetic Recording is inherently well-suited to achieving high TPI values, and its benefits are magnified when combined with advanced coding strategies and HAMR. Even in conventional ePMR environments, joint modulation and LDPC code optimization yields measurable areal density improvements, providing a viable path to extend ePMR product life at higher densities.

When these same coding optimizations are applied within ePMR SMR environments, further gains are realized. However, the most compelling opportunities arise when these techniques are paired with HAMR. With the ability to reduce track pitch via laser current control, HAMR enables significantly denser track layouts. In this regime, SMR recording further amplifies the gains achieved through optimized coding, surpassing 1 million TPI with ease.

As track pitch continues to shrink, the BAR naturally decreases, and inter-track interference (ITI) becomes a dominant noise source. In this high-ITI regime, additional areal density gains are achieved by explicitly equalizing interference from adjacent tracks. If modulation and LDPC codes are re-optimized for this interference-equalized environment, the cumulative gain is substantial — as highlighted in Figure 4, where SMR with ATE (adjacent-track equalization) delivers a total improvement of over 60% compared to the Conventional Magnetic Recording (CMR) baseline.

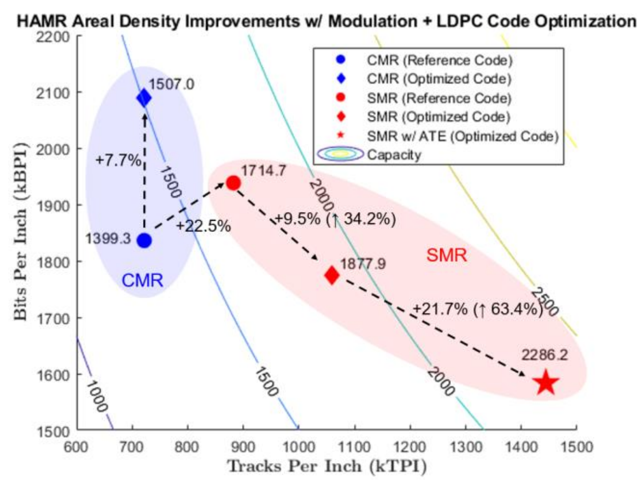

Fig. 4. Areal density achieved across HAMR CMR and SMR recording modes using reference and optimized modulation + LDPC codes. The final point reflects further gain from SMR with adjacent-track equalization (ATE). All data shown are measured under identical test conditions

These results highlight how continued gains in TPI are driving the BAR steadily closer to 1.0—a trend that opens the door to new architectural strategies for sustaining areal density growth. Together, these findings reinforce that the HDD remains a vibrant and evolving platform for innovation.

REFERENCES

[1] Galbraith, R., “Use of Mutual Information as a Channel Metric”, TMRC 2024

[2] Shannon, C.E., “A Mathematical Theory of Communication”. Bell System Technical Journal, 27, 379-423