Improved Data Recovery from Patterned Media With Inherent Jitter Noise Using Low-Density Parity-Check Codes

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Patterned magnetic media promises areal densities in excess of 1 Tbit/in^2 for data storage. However, current imperfect patterning techniques result in a variation in the dimensions and distribution of the fabricated islands. As a result, this variation introduces jitter in the replay waveform that makes data recovery difficult. In this paper, we investigate the use of low-density parity-check (LDPC) codes and iterative decoding for mitigating the effects of lithography jitter and improving the read channel performance in patterned media storage systems. In addition, we show that the adoption of LDPC coding techniques permits an increase in the data storage capability of the medium to approximately 1.6 Tbit/in^2 with acceptable bit-error-rate performance.

***Index Terms*—Lithography jitter, low-density parity-check (LDPC) codes, perpendicular patterned media, read channel performance.**

I. Introduction

THE general view is that the use of a continuous thin-film storage medium in current magnetic data storage systems will be unsuitable for attaining storage densities in excess of 1 Tbit/in^2, due to the onset of thermal stability issues at ultra-high storage densities [1], [2]. As such, new storage technologies, such as the use of a patterned magnetic storage medium, must be explored [1]. However, the development of patterned magnetic media as a viable storage solution is currently limited by the availability of efficient and cost-effective fabrication techniques, capable of producing uniform, nanometer-sized islands, regularly spaced over large areas. As a result of the limitations of existing fabrication techniques, there is an inherent variation in the size and position of the fabricated islands. If the islands are sufficiently small to exhibit single domain behavior then, as a consequence of the variation in island geometry media, noise in patterned media is dominated by lithography jitter [1], [3]–[6], unlike perpendicular continuous media where transition noise is dominant [7]. The effect of lithography jitter, which can be shown to be Gaussian in nature [8], is to degrade the replay waveform and make the reliable recovery of stored data more difficult [9].

There have been a number of published works addressing the issue of data recovery and channel designs for patterned media [2], [9]–[13]. Early studies by Hughes have investigated read channel designs for patterned media [2], [10]. A study by Nair and New [11] investigated how island edge imperfections were a cause of noise in patterned media recording. Nutter *et al.* investigated how the island geometry affected the replay waveform and data recovery process [9], [13]. Recent work by Hu *et al.*, makes a comparison between various coding and iterative decoding schemes in patterned media storage systems [12], including simple convolutional codes, turbo codes, and low-density parity-check (LDPC) codes. This work demonstrated that the incorporation of coding and iterative decoding techniques leads to a significant coding gain. However, this work failed to take into account the significant signal degradations introduced as a result of the presence of lithography jitter.

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In this paper, we concentrate on the application of LDPC codes and iterative decoding techniques to magnetic storage systems incorporating a patterned magnetic storage medium, for the more realistic case where lithography jitter is present. We demonstrate that the adoption of LDPC codes and iterative decoding offers a means of improving the read channel bit-error-rate (BER) performance in the presence of lithography jitter. In addition, an acceptable BER performance can be observed even when the storage density of the medium is increased to 1.6 Tbit/in^2 (reduced island periodicity/track period of 20 nm) for the same giant magnetoresistive (GMR) read head configuration.

This paper is organized as follows. Section II introduces the simulations that have been developed in order to model the replay and data recovery processes in a patterned media storage system, as well as the application of LDPC coding techniques. In Section III, the effect of lithography jitter on the BER performance of the read channel is investigated, with and without the use of LDPC codes. Finally, Section IV summarizes conclusions arising from the work undertaken.

II. Read Channel Simulation

The performance of the read channel in a storage system incorporating a patterned magnetic storage medium has been evaluated using MATLAB simulations of the replay and data recovery processes. Fig. 1 illustrates the structure of the complete read channel simulated, which consists of three functional blocks (illustrated as shaded boxes): the replay model, the data recovery channel, and the LDPC encoder/decoder. The structure and simulation of each of these functional blocks are described below.

A. Replay Model

The replay model predicts the signal waveform that would be observed from a GMR read sensor as it scans along a track of islands in a magnetic storage system incorporating a patterned perpendicular magnetic storage medium. The replay model is based on an extension of the standard two-dimensional (2-D) reciprocity approach to three-dimensional (3-D) space and takes into account the geometrical aspects of both the patterned recording medium and the GMR read sensor used. The complete modeling process is outlined in more detail in [13] and is covered briefly below.

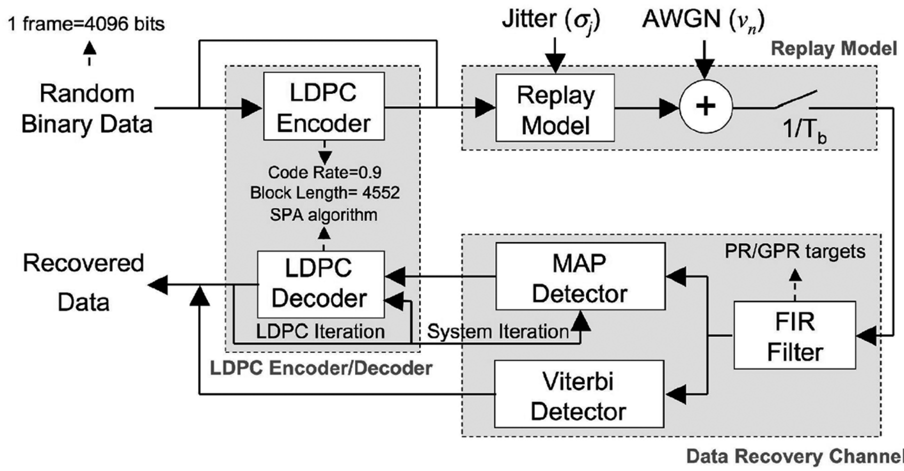

Fig. 1. Block diagram of the complete read channel simulation. The three functional blocks of the simulation are shown in the shaded boxes: the replay model, the data recovery channel, and the LDPC encoder/decoder.

The voltage signal from the GMR read head is proportional to the signal flux injected into the GMR sensor at the air-bearing surface (ABS). Hence, when the read head is at position $\bar{x}$ along the scan direction, x, the signal flux at the GMR sensor, $\Phi_{\rm sig}$, is given by

$$\Phi_{\rm sig}(\bar{x}) = \mu_o \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left[\int_{d}^{d+\delta} -\frac{\partial\phi(x,y,z)}{\partial y}dy\right] \times M_y(x-\bar{x},z)\,dx\,dz \quad (1)$$

where ϕ is the scalar magnetic field potential, which varies in the along-track direction, x, the across-track direction, z, and the position below the ABS of the GMR read head, y. M_y is the perpendicular magnetization component of the medium, which varies in the along-track, x, and across-track, z, directions only.

Equation (1) can be expressed in the form

$$\Phi_{\rm sig}(\bar{x}) = \mu_o\{{\rm IFT}[\hat{M}_y^*(k_x,k_z).\hat{\phi}(k_x,d,k_z)] - {\rm IFT}[\hat{M}_y^*(k_x,k_z).\hat{\phi}(k_x,d+\delta,k_z)]\} \quad (2)$$

where M_y: $\hat{M}_y$ and ϕ: $\hat{\phi}$ are Fourier transforms pairs, $\hat{M}_y^*$ is the complex conjugate of $\hat{M}_y$, IFT is the inverse Fourier transform operation, and k_x and k_z are the Fourier transform wavenumbers in x and z directions, respectively. Thus, the calculation of the voltage signal from the GMR read head is simply a Fourier transform process involving the magnetization distribution across the plane of the storage medium, and simulated potential distributions below the ABS of the GMR read sensor.

The 2-D potential distribution along the plane of the ABS is calculated using the analytical approach of Wilton [14]. In the following analysis, a patterned perpendicular magnetic storage medium with no SUL has been adopted, as this media configuration has been shown to offer optimum read channel performance [9]. In this case, projected potential distributions at any plane below the ABS, as required for (2), can be calculated using the simple filter function [9], [14]

$$\hat{\phi}(k_x,y,k_z) = \hat{\phi}(k_x,0,k_z)\exp(-\kappa y) \quad (3)$$

where $\kappa = \sqrt{k_x^2+k_z^2}$.

In this analysis the medium magnetization and potential distributions are calculated over an area 20.48 nm $\times$ 20.48 nm below the center of the GMR read sensor, and are represented using matrices of dimensions 2048×2048 at a spatial resolution of 0.1 nm (in both along track and across track directions).

Once the recorded magnetization pattern in the storage medium has been generated, such as an isolated magnetic island, then the 3-D reciprocity model can be used to predict the output response to that magnetic structure. More importantly, the model allows the generation of a readout waveform including the presence of inter-track interference (ITI) introduced as a result of the read head sensing islands along tracks adjacent to the main data track. The inclusion of ITI is pertinent in patterned media storage systems where the bit-aspect-ratio (BAR) may very well be 1 due to the patterning processes used typically producing square or circular islands.

If data is recorded to a patterned medium such that each island is used to store a single recorded bit, then the replay waveform due to a train of random recorded data is produced by the superposition of an ideal step response, generated for an isolated island using the 3-D reciprocity model described. This process involves the superposition of the step response at points in the replay waveform corresponding to the ideal physical location of the leading and lagging edges of each island as the GMR read head scans along a track of islands. As lithography jitter leads to variations in the position of the edges of each island, it is easily introduced into the simulated replay waveform by varying the position at which the step response is superposed. Here, the random shift in the edge position due to lithography jitter is defined to be a Gaussian distribution [8] of zero mean and variance σ_j^2, where σ_j is specified in nanometers from the ideal position of the island edge. The Gaussian distribution in this case is truncated so that the edge shift introduced is no greater than the separation between islands. Jitter is added in the along-track direction only, as jitter across-track has little effect on the replay signal due to the relatively large read sensitivity function of the head compared with the track width [11].

The effect of ITI is easily introduced into the simulated replay waveform as a result of adopting the 3-D reciprocity model described [13], [15]. Replay waveform contributions due to the read head sensing adjacent tracks are calculated independently in a similar manner to that used to generate the signal from the main data track. However, in this case the step response used in the superposition process is evaluated with the read head displaced off-track by a track pitch. The replay waveform with ITI is then the linear sum of the isolated signal contributions from three tracks: the main track and the two adjacent tracks either side of the main track.

A replay waveform of specific signal-to-noise ratio (SNR) is produced by adding additive white Gaussian noise (AWGN) to the simulated replay waveform with rms noise voltage, v_n, defined by

$$\mathrm{SNR(dB)} = 20 \cdot \log_{10}\left(\frac{v_{0-p}}{v_n}\right) \tag{4}$$

where v_{0-p} is the peak signal of the simulated replay waveform due to a spread of random data [4].

The noisy signal, which now approximates a realistic replay waveform, is then sampled at the channel data rate $1/T_b$, where T_b is the island period, such that the data samples are extracted from the replay waveform at (assumed ideal) points corresponding to the position of the center of each island along the main data track. The replay samples are then passed to the data recovery channel simulation in order to recover the recorded data.

In the following analysis, the input data to the read channel simulation is a randomly generated 4096-bit frame of random data.

B. Data Recovery Channel Simulation

The data recovery channel, as illustrated in Fig. 1, consists of a finite-impulse response (FIR) filter, for signal equalization, followed by either a Viterbi detector, in the case of a partial-response maximum-likelihood (PRML) read channel, or a MAP detector, in order to transmit bit probabilities to the LDPC decoder when LDPC codes are adopted.

In the simplest scenario, where no coding scheme is employed, the data recovery channel is a simple PRML channel consisting of an FIR filter followed by a Viterbi detector. Here, the sampled data sequence is equalized by the FIR filter such that the resulting equalized data sequence closely resembles the ideal sample values generated using a desired target filter, such as a partial-response (PR) or generalized partial-response (GPR) target. In the case of a PR target, the FIR coefficients are found using the least-mean-square (LMS) algorithm for a known data sequence at a specified SNR value. In the case of a GPR target, both the GPR target and FIR filter coefficients are found simultaneously following the method described in [16]. Following equalization, the recorded data are recovered from the equalized data samples using a Viterbi detector.

In the case where the use of LDPC codes is investigated, the LDPC encoder and the LDPC decoder are added to the channel simulation, and the Viterbi detector is replaced with a MAP detector in order to transmit bit probabilities to the LDPC decoder. The GPR target and FIR filter are still optimized and used in the same manner as in the PRML channel.

The performance of the read channel is evaluated via plots of the BER of the recovered data against replay waveform SNR, as defined by (4). The BER is calculated as the ratio of the number of bits recovered in error divided by the total number of bits that have been processed through the read channel. A decision as to whether a recovered bit is in error is made by comparing the data bits at the output of the Viterbi detector, or the LDPC decoder, with the known input data. Replay waveforms are generated for repeated frames of data (4096 uncoded bits) for each specific SNR value, which are processed by the read channel, and the total number of bits in error is counted. In order to make a reasonable measure of the BER, the simulation stops, and the BER is calculated, when a minimum of 10 frames are found to contain one or more recovered bits in error.

C. LDPC Codes

LDPC codes, which are iteratively decoded, have been selected as the most appropriate error correction codes for a recording system incorporating a patterned storage medium, due to the significant enhancement in the performance they offer in continuous media. Related work that does not include the effect of jitter also concludes that significant gain is achievable using error correction codes, like LDPCs [12]. The error correction codes used in this paper have linear encoding time, high rate, and good performance when iteratively decoded, especially with this channel model.

The LDPC codes used are irregular codes constructed with a zigzag parity pattern [17], resulting in linear-time encoding complexity. They are constructed in such a way so as to maximize the girth of the underlying Tanner Graph of the decoder using the progressive-edge-growth (PEG) algorithm [18]. The parity-check matrix of the LDPC codes is split into two partitions, referred to as parity, H_p, and information, H_i, sections, i.e., $H = [H_p H_i]$. The LDPC codes used are of code rate 0.9, with parity length of 456, information length of 4096, and resulting code length of 4552. Assuming that $h^p_{i,j}$ and $h^i_{i,j}$ are used to denote the ith row and jth column of H_p and H_i, respectively, then if H_p is of zigzag pattern, then $h^p_{i,j} = 1$ for both $i = j$ and $i + 1 = j$, where $0 \le i, j < n - k$. A codeword, denoted as c, can be partitioned in a similar manner, $c = [pi]$, where p are the parity bits, $p = (p_0, p_1, \ldots, p_{n-k-1})$, and i are the information bits, $i = (i_0, i_1, \ldots, i_{k-1})$. The encoding process can be accomplished using

$$p_0 = \left(\sum_{j=0}^{k-1} h^i_{0,j} i_j\right) \bmod 2 \tag{5}$$

and

$$p_i = \left(\sum_{j=0}^{k-1} h^i_{i,j} i_j + p_{i-1}\right) \bmod 2, \quad \text{for } i \in \{1, 2, \ldots, n-k-1\}. \tag{6}$$

The LDPC decoder is implemented using the sum-product algorithm (SPA), where the LDPC decoder receives the *a posteriori* probabilities (APP) from the channel MAP detector and generates the APPs of the recovered data. We define an *LDPC iteration* as the passing of extrinsic information from the output of the LDPC decoder to its input, whereas a *system iteration* is the feedback of extrinsic information from the output of the LDPC decoder to the input of the MAP detector. For the system simulated, five LDPC iterations and two system iterations have been found to offer the best compromise between number of iterations and read channel performance.

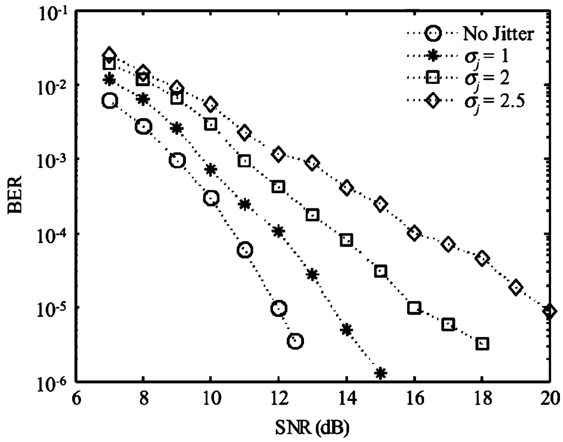

Fig. 2. Plots of BER against SNR for varying lithography jitter with no coding scheme adopted at a storage density of 1 Tbit/in^2 (σ_j in nm).

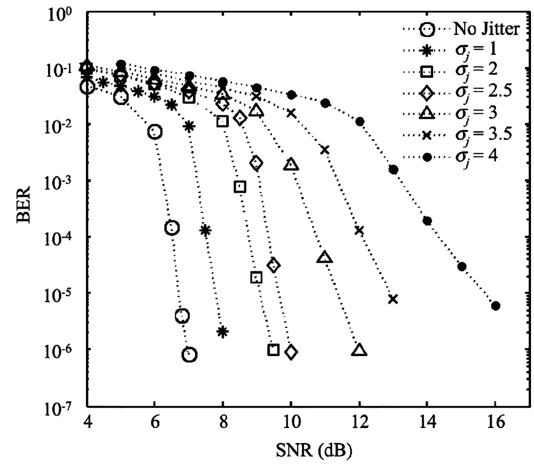

Fig. 3. Plots of BER against SNR for varying amounts of lithography jitter with LDPC codes adopted (σ_j in nm). Here, the code rate loss is taken into account by increasing the storage density to 1.27 Tbit/in^2.

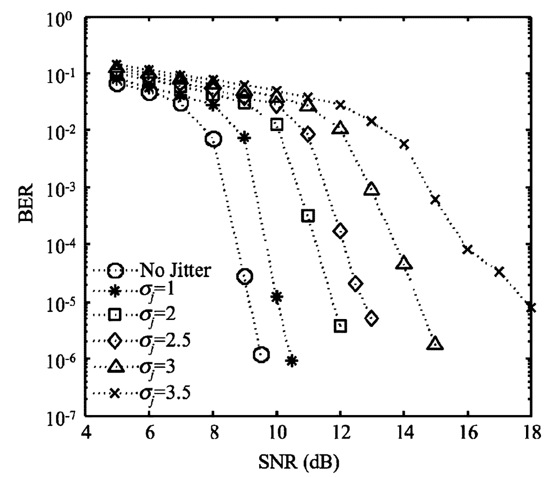

Fig. 4. Plots of BER against SNR for varying lithography jitter when LDPC codes are taken into account for a storage density of 1.6 Tbit/in^2 (σ_j in nm).

III. Results

In the following analysis, a theoretical GMR read head with a read sensor of width 20 nm (across track), length 4 nm (along track), and shield-to-shield spacing 16 nm has been used. The patterned perpendicular recording medium is of thickness 10 nm and its top surface is placed 10 nm below the ABS of the read head. It has been shown that for the specific media/head configurations adopted, a patterned medium with no SUL offers overall better BER performance compared to a patterned medium employing a SUL [9]. In addition, the performance is improved significantly through the use of hexagonally packed islands [15]. Hence, a magnetic storage medium with no SUL and the islands hexagonally packed has been adopted in this analysis. Initially, the length/width of the square islands is 12.5 nm and the period/track pitch is 25 nm, corresponding to an areal density of 1 Tbit/in^2. The islands are assumed to be single domain, which is a valid assumption at such dimensions [19], such that media noise is dominated by lithography jitter.

The data recovery channel contains a 7-tap FIR filter that is used to equalize the replay data samples to an optimized GPR target of length 5, which have been shown to be sufficient for improved channel performance in the case of perpendicular recording [20]. The optimized GPR target for the system was $[1 - 0.35 - 0.32 - 0.29 - 0.01]$, which was found at an SNR of 10 dB, with no lithography jitter present, using the approach detailed in [16]. In the following discussion, we define an acceptable BER to be $< 10^{-5}$.

Fig. 2 illustrates plots of BER against SNR in the case of no coding scheme employed for varying amounts of increased lithography jitter.

It is evident from Fig. 2 that the read channel can tolerate the presence of jitter with up to $\sigma_j = 2.5$ nm while still maintaining an acceptable BER performance. However, any further increase in the amount of jitter results in a severe degradation of the BER performance (not shown). Hence, jitter with $\sigma_j = 2.5$ nm is the maximum the system can tolerate with no coding scheme employed.

In Fig. 3, the advantage of using LDPC codes to improve the BER performance in the presence of lithography jitter is demonstrated. In order to take into account the code rate loss due to the presence of the LDPC code, the island geometry and period/track pitch have been scaled by the code rate, which for a code rate of 0.9, requires a reduction of the island period and island size to 22.5 nm and 11.25 nm, respectively, resulting in a storage density of 1.27 Tbit/in^2.

In the case where no lithography jitter is present, the use of LDPC codes results in approximately 5.5 dB improvement in the SNR that can be tolerated for an acceptable BER, compared to the uncoded case (Fig. 2). In the case of lithography jitter with $\sigma_j = 2.5$ nm, the gain in allowable SNR extends to approximately 10 dB when adopting LDPC codes while still achieving an acceptable BER; the acceptable SNR in this case is over 2 dB less than that of the uncoded case with no jitter present. In addition, it is clear that by incorporating LDPC codes, the system can tolerate lithography jitter with $\sigma_j = 4$ nm and still achieve an acceptable BER at a minimum SNR of 16 dB.

Fig. 4 illustrates BER against SNR curves for varying amounts of lithography jitter when the island period and track pitch have been scaled to 20 nm, leading to an increase of the areal density to 1.6 Tbit/in^2. In this case the island length and width have been kept at 12.5 nm, leading to increased inter-symbol-interference (ISI) in the replay signal waveform due to the reduced separation between islands.

It is clear from Fig. 4 that an acceptable BER performance can still be achieved even with increased ISI present. Here, an acceptable BER can be observed at an SNR of approximately 9 dB with no lithography jitter present, whereas in the uncoded case at the same storage density (not shown) the BER performance is unacceptable, even with no lithography jitter present. Fig. 4 demonstrates that the read channel can tolerate up to $\sigma_j = 3.5$ nm of jitter while still maintaining an acceptable BER performance.

IV. Conclusion

Using a novel simulation of the readout process in a patterned magnetic media storage system and a comprehensive simulation of the data recovery channel, we have demonstrated that the use of LDPC codes offers one way of achieving acceptable BER performance in a 1 Tbit/in^2 patterned media storage system. The introduction of jitter arising due to imperfections introduced by the nonperfect lithography process can have a significant impact on the BER performance of the read channel. However, the adoption of LDPC coding techniques allows the presence of lithography jitter to be tolerated while still maintaining an acceptable BER performance. Results have been presented illustrating the read channel performance using curves of BER against read waveform SNR, with and without the use of an LDPC coding scheme, with varying amounts of lithography jitter present.

The introduction of lithography jitter has a detrimental effect on the performance of the conventional PRML read channel, in particular when no LDPC coding scheme is adopted. By adopting LDPC coding techniques the maximum amount of jitter noise that can be tolerated can be increased from $\sigma_j = 2.5$ nm (with no LDPC code) to $\sigma_j = 4$ nm (with the LDPC code at an increased storage density of 1.27 Tbit/in^2) while still maintaining acceptable BER performance.

This work supports the viability of patterned media as a possible future storage medium, and more specifically demonstrates that the adoption of LDPC codes and iterative decoding techniques should be considered to alleviate the detrimental effect that lithography jitter has on the reliable recovery of stored data. The use of LDPC codes is one example of a range of iterative architectures available. Future work will concentrate on the investigation of other suitable iterative coding schemes [21] and their application, with an emphasis on the comparison of these architectures with respect to read channel performance, complexity, robustness, and applicability [22] in patterned media storage systems. The use of noise prediction methods [23] and alternatives, such as SNR mismatch methods [24], which have the potential to further improve the performance of the read channel, are also being investigated.

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