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Investigation of Iterative TA Suppression Method in Perpendicular Recording System

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Abstract— **Thermal asperities (TAs) cause a critical problem in perpendicular recording systems because they can distort the readback signal to the extent of causing an error burst in data detection process. System performance without a TA detection and correction algorithm can be unacceptable, depending on how severe the TA effect is. This paper investigates the performance of an iterative TA suppression method, which jointly performs TA suppression and turbo equalization on coded partial-response channels. Specifically, two iterative TA suppression methods are compared (i.e., one is based on a threshold-based technique, and the other is based on a least-squares (LS) fitting technique) in terms of bit-error rate performance and complexity. Results indicate that two methods have comparable complexity, but the method based on a LS fitting technique performs better than that based on a threshold-based technique. Thus, it is worth employing the iterative TA suppression method based on the LS fitting technique in perpendicular recording systems.**

***Index Terms*—Coded partial-response channel, iterative method, thermal asperity detection and correction, turbo equalization.**

I. Introduction

To achieve ultra high storage capacity, magnetic recording systems use the magneto-resistive (MR) read head instead of the inductive heads. Practically, the MR read head directly senses flux via the transitions of the magnetic pattern written on the disk surface, resulting in an induced voltage pulse called a *transition pulse*. When an asperity (or a surface roughness) comes into contact with the slider, both the surface of the slider and the tip of the asperity are heated, which results in an additive voltage transient known as *thermal asperity* (TA) [1] in the readback signal.

In general, the TA is considered as a defect. If the read head hits a dust particle, a long TA will occur, producing a severe transient noise burst, loss of timing synchronization, or even off-track perturbation. Typically, a TA signal has a short rise time (50 – 160 ns) with a long decay time (1 – 5 μs), and its peak TA amplitude could be 2 to 3 times the peak of the readback signal [1].

Several TA detection and correction algorithms have been proposed in the literature [2] – [7] to alleviate the TA effect. The average value of the normal readback signal is zero, whereas that of the TA-affected readback signal is not because the TA causes a shift in the baseline of the readback signal. Thus, Klaassen and van Peppen [2] proposed the TA detection that looks at the baseline of the averaged readback signal, while the TA correction was done by use of a high-pass filter. Dorfman and Wolf [3] proposed a method to reduce the TA effect by passing the TA-affected readback signal through a filter (1 – D), where D is a delay operator. This method is good for a longitudinal recording channel, but not for a perpendicular recording channel because this channel has a d.c. component. For perpendicular recording channels, Erden and Kurtas [4] proposed a TA suppression method by use of different low-pass and high-pass filters, while Mathew and Tjhia [5] proposed a simple threshold-based technique to detect and suppress the TA effect, Kovintavewat and Koonkarnkhai [6] proposed a TA suppression method based on a least-squares fitting technique, which performs better than the method proposed in [5] at the expense of increasing complexity.

All TA suppression methods mentioned above were proposed for the system without ECCs. Because of a large coding gain of ECCs, a reliable communication can be operated at very low signal-to-noise ratio (SNR) [8]. This means that the TA suppression method must be performed at an SNR lower than ever before. Therefore, a conventional receiver, which performs TA suppression and turbo equalization *separately*, is doomed to fail when the SNR is low enough. To solve this problem, Kovintavewat and Koonkarnkhai [7] proposed an iterative TA suppression method based on a least-squares fitting technique, to *jointly* performing TA suppression and

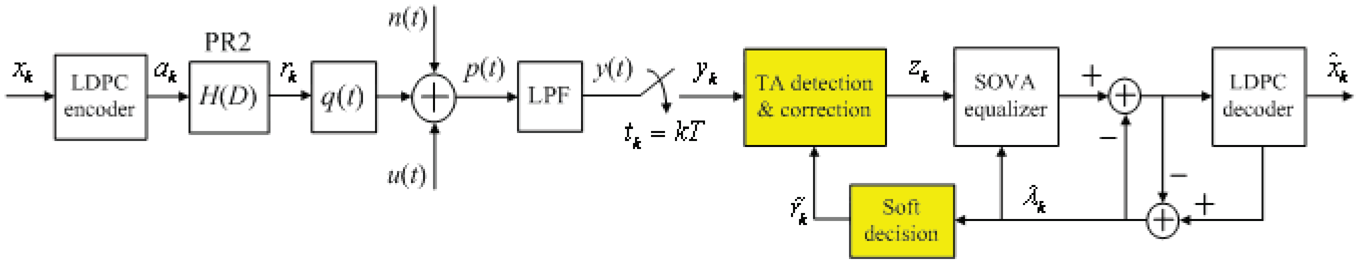

Fig. 1. A channel model with an iterative TA suppression method.

turbo equalization [9]. This paper investigates and compares the performance of the iterative TA suppression methods based on a least-squares fitting technique and a threshold-based technique in terms of bit-error rate (BER) and complexity.

The paper is organized as follows. After explaining a system model in Section II, Section III briefly describes how the iterative TA suppression method works. Section IV summarizes the iterative TA suppression method. Complexity issue is given in Section V. Numerical results are provided in Section VI. Eventually, Section VII concludes this paper.

II. Channel Model

Consider a rate-8/9 coded partial-response (PR) channel illustrated in Fig. 1, where a block of 3640 message bits $x_k \in \{0, 1\}$ is encoded by a regular $(j, k) = (3, 27)$ low-density parity-check (LDPC) code [10], resulting in a coded block length of 4095 bits $a_k \in \{\pm 1\}$ with bit period T. The parity-check matrix has 3 ones in each column and 27 ones in each row. The readback signal can then be expressed as

$$p(t) = \sum_k r_k q(t - kT) + n(t) + u(t), \quad (1)$$

where $r_k = a_k * h_k \in \{0, \pm 2, \pm 4\}$ is the noiseless channel output, $*$ is the convolution operator, $q(t) = \sin(\pi t/T)/(\pi t/T)$ is an ideal zero-excess-bandwidth Nyquist pulse, $n(t)$ an additive white Gaussian noise (AWGN) with two-sided power spectral density $N_0/2$, and $u(t)$ is a TA signal.

A widely used TA model described by Stupp *et al.* [1] is considered in this paper as shown in Fig. 2, because it fits captured spin stand data and drive data very well [4]. This TA signal has a short rise time with a long decay time, and its effect is assumed to decay exponentially, which can be modeled as

$$u(t) = \begin{cases} A_0 t / T_r, & 0 \le t \le T_r \\ A_0 \exp\left(-\left(t - T_r\right)/T_d\right), & T_r < t \le T_f \end{cases} \quad (2)$$

where $A_0 = \beta \sum_k |h_k|$ is the peak TA amplitude, $\beta \ge 0$ is the peak-factor, T_r is a rise time, and T_d is a decay constant. In this paper, the TA duration is assumed to be $T_f = T_r + 4T_d$ [5], where a decay time of $4T_d$ is sufficient because it will reduce the amplitude of the TA signal to approximately 1.8% of its peak amplitude.

At the receiver, the readback signal $p(t)$ is filtered by an ideal low-pass filter (LPF), whose impulse response is $q(t)/T$, to eliminate out-of-band noise, and is then sampled at a symbol rate of 500 Mbps [5], assuming perfect synchronization. The sampler output, y_k, is fed to the TA detection/correction block to obtain the corrected readback signal, z_k.

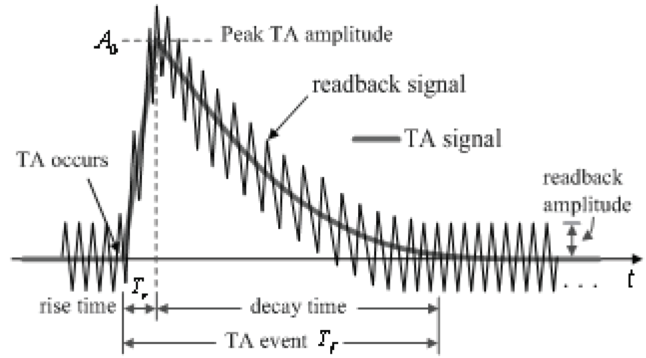

Fig. 2. A widely used TA model associated with the MR read head.

In a conventional setting, the TA detection/correction block is followed by a turbo equalizer, which iteratively exchanges soft information between the soft-output Viterbi algorithm (SOVA) [11] equalizer for the PR2 channel and the LDPC decoder (implemented based on the message-passing algorithm [11] with $N_{in} = 3$ internal iterations) for the outer code.

III. Existing TA Suppression Method

This paper focuses only on two TA suppression methods (i.e., one is based on a threshold-based technique, and the other is based on an LS fitting technique) because of its simplicity. We briefly explain how the two methods operate as follows:

A. Based on a Threshold-Based Technique

We denote the TA suppression method based on a threshold-based technique [5] as "**M1**," where the TA detection method is performed by first finding the average value of the readback signal, q_k, according to

$$q_k = \frac{1}{L} \sum_{i=k-\alpha}^{k+\alpha} y_i \quad (3)$$

where y_i is the i-th sample of the readback signal, α is an integer, and $L = 2\alpha + 1$ is the window length for computing q_k. Then, a TA is detected if $q_k \ge n_1$ and $y_i \ge n_2$ for a few consecutive samples, where n_1 *and* n_2 are threshold values.

After the TA is detected, the TA detection operation is disabled and the TA correction operation is activated for a duration of T_f. Then, the TA-unaffected readback signal, z_k, is obtained by subtracting the reconstructed TA signal from the TA-affected readback signal according to

$$z_k = \begin{cases} y_k - q_k, & \text{if TA is present} \\ y_k, & \text{if TA is absent} \end{cases}. \tag{4}$$

B. Based on a Least-Squares Fitting Technique

Again, we denote the TA suppression method based on the LS fitting technique [6] as "**M2**." To detect a TA, we first find the averaged readback signal, q_k, from (3). Then, the TA is detected if only $q_k \geq n_1$.

After the TA is detected, the TA detection operation is disabled and the TA correction operation is activated for a duration of T_f so as to construct the estimated TA signal, $\hat{u}(t)$, based on the LS fitting technique and the samples $\{q_k\}$ [6]. This can be achieved by estimating the TA signal during a rise time and a decay time, where the TA signal during a rise time is approximately linear, whereas that during a decay time is exponentially decay [1]. Hence, the corrected readback signal is obtained from (4) by replacing q_k by $\hat{u}_k$, where $\hat{u}_k = \hat{u}(kT)$ is the k-th estimated TA sample.

IV. Iterative TA Suppression Method

A conventional receiver sends a sequence $\{z_k\}$ directly to the turbo equalizer. Specifically, the TA suppression method ignores the presence of ECCs, and is thus doomed to fail when the SNR is low enough. To solve this problem, the iterative TA suppression method was proposed in [7], where the TA detection/correction block, the SOVA equalizer, and the LDPC decoder exchange information as shown in Fig. 1. This paper investigates the performance of the two iterative TA suppression methods, one is based on M1 and the other is based on M2.

Denote the first time that the SISO decoder outputs the soft information λ_k as the *first* iteration. Clearly, the iterative scheme performs the same operations as the conventional receiver does at the first iteration. Nevertheless, after the first iteration, the soft information λ_k is fed back to both the SOVA equalizer and the TA detection/correction block. Then, an improved set of samples $\{z_k\}$ can be obtained by running the TA suppression method again, but this time it is performed on a sequence $\{c_k\}$, where $c_k = y_k - \tilde{r}_k$, $\tilde{r}_k = E[r_k|\lambda_k]$ is the k-th soft decision of r_k, and $E[\cdot]$ is the expectation operator. It can be shown that for a PR2 channel, the soft decision is given by [7]

$$\tilde{r}_k = \frac{A+B+C}{2\cosh(\lambda_k/2)\cosh(\lambda_{k-1}/2)\cosh(\lambda_{k-2}/2)} \tag{5}$$

where $A = 2\sinh((\lambda_k + \lambda_{k-1} + \lambda_{k-2})/2)$, $B = \sinh((\lambda_k + \lambda_{k-1} - \lambda_{k-2})/2)$, and $C = \sinh((-\lambda_k + \lambda_{k-1} + \lambda_{k-2})/2)$. Consequently, the improved samples $\{z_k\}$ are fed to the turbo equalizer, which generally yields an improved set of soft decisions $\{\tilde{r}_k\}$. The process repeats as many turbo iterations as required. It is evident that

Table 1: The total number of operations (per bit) of each function.

Module	Number of operations (**per bit**)	
	Addition	Multiplication
SOVA	$7Q + \frac{\delta^2+9\delta+9}{2} + 1$	$6Q + 1$
LDPC decoder	$(1 + (k-1)(1-R))N_{\text{in}} + 1$	$(1-R)N_{\text{in}}$
Data exchange	2	0
Soft decision	8	9
M1	$(L-1) + T_f/P + C$	1
M2	$\{(L-1)P + 14T_d + 5T_r + T_f - 11\}/P + C$	$\{P + 18T_d + 2T_r + 11\}/P$

Table 2: Complexity (per bit) of different iterative TA suppression methods.

System	Number of operations (**per bit**)	
	Addition	Multiplication
Conventional receiver with M1	$50.251 + 222.17N$	$1 + 25.333N$
Iterative TA with M1	$(280.42 + C)N$	$35.333N$
Iterative TA with M2	$(283.87 + C)N$	$39.744N$

the turbo equalizer benefits from better samples $\{z_k\}$, and the TA suppression method benefits from better decisions $\{\tilde{r}_k\}$.

V. Complexity Comparison

To measure the complexity of iterative schemes, we consider the total number of additions and multiplications (per bit) as a criterion. Table 1 shows the complexity of each component, where $Q = 2^\nu$ is the number of trellis states [12]; ν is the target memory; δ is the decoding depth used in SOVA [11]; k is a parameter of an LDPC code [10]; N_{in} is the internal iterations used in the LDPC decoder; R is a code rate; P is the number of bits per sector, C is an indicator such that $C = 0$ if $N = 1$, and $C = 1$ if $N > 1$, and N is the number of turbo iteration. For a coded PR2 channel, the complexity of each iterative TA suppression methods is given in Table 2, where $\nu = 2$, $Q = 4$, $L = 51$, $\delta = 15$, $N_{in} = 3$, $k = 9$, $T_d = 1000T$, $T_r = 30T$, $T_f = 1030T$, $R = 8/9$, and $P = 4095$ bits.

It is of interest to compare the performance of different TA suppression methods when they have same complexity. Since multiplication has much more complexity than addition in terms of circuit implementation, we consider only the number of multiplications when comparing performances. Suppose that current technology can support the total number of multiplications equal to 10 iterations of the iterative TA suppression method with M2. It is clear from Table 2 that 10 iterations of the iterative TA suppression method with M2 are approximately equal to 11 iterations of that with M1, and 14 iterations of the conventional receiver (which utilizes the M1 to mitigate the TA effect at the first iteration only).

VI. Numerical Result

In simulation, every 4095-bit data sector is corrupted by one TA at the 500-th bit with $\beta = 2$, $T_r = 60$ ns, and $T_d = 0.5$ μs (i.e., a TA event $T_f = 1030T$) [5]. We compute the BER based on a minimum number of 10000 data sectors and 1000 error bits, and call that number as "BER given TA." For the PR2 channel, L = 51, $n_1 = 2.8$, and $n_2 = 4.5$ are suitable parameters for TA detection [6, 7].

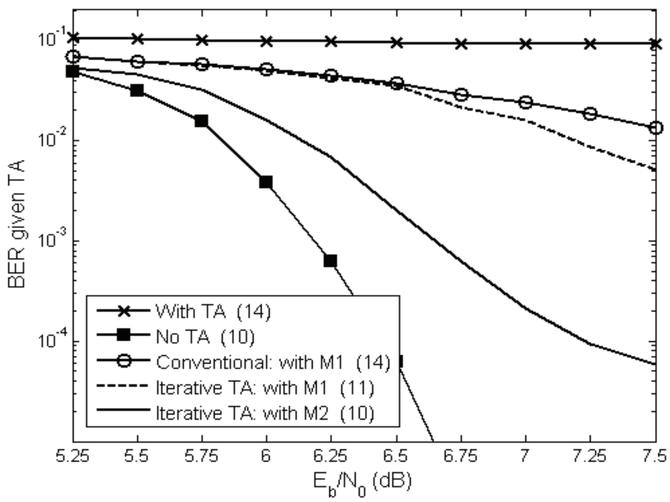

Fig. 3. Performance comparison of different schemes with same complexity.

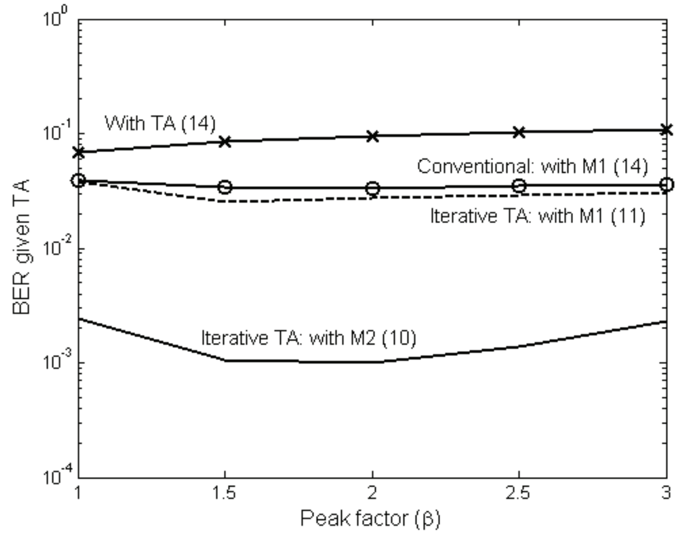

Fig. 4. BER performance with different peak factors.

Fig. 3 compares the performance of different schemes when they have *same* complexity, where the number inside the parenthesis indicates the number of iterations used to generate each curve, and the system performance in the absence of TA is referred to as "No TA." It is obvious that without the TA suppression method, the system performance is unacceptable, denoted as "With TA." As depicted in Fig. 3, the iterative TA suppression method with M2 outperforms that with M1 and the conventional receiver.

We also compare the performance of different schemes as a function of peak factors in Fig. 4. As expected, with same complexity, the iterative TA suppression method with M2 still outperforms that with M1 and the conventional receiver for all peak factors. This might be because the TA suppression method based on the LS fitting technique (i.e., M2) performs better than that based on the threshold-based technique (i.e., M1) as studied in [6].

VII. Conclusion

The TA effect can distort the readback signal to the extent of causing a sector read failure. Clearly, an iterative TA suppression method, which performs TA suppression and turbo equalization jointly, outperforms a conventional receiver with separate TA suppression and turbo equalization, especially when SNR is low. This paper investigates the performance of two iterative TA suppression methods based on the threshold-based technique (i.e., M1) and the LS fitting technique (i.e., M2).

Although M2 has more complexity than M1, it turns out that when the complexity is limited to a low-to-moderate amount, the iterative TA suppression method using M2 performs better than that using M1 and the conventional receiver. Thus, the iterative TA suppression method using M2 is more attractive for applications with strict complexity constraints.

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References

[1] S. E. Stupp, M. A. Baldwinson, P. McEwen, T. M. Crawford, and C. T. Roger, "Thermal asperity trends," *IEEE Trans. Magn*., vol. 35, no. 2, pp. 752 – 757, March 1999.

[2] K. B. Klaassen and J. C. L. van Peppen, "Electronic abatement of thermal interference in (G)MR head output signals," *IEEE Trans. Magn*., vol. 33, pp. 2611 – 2616, September 1997.

[3] V. Dorfman and J. K. Wolf, "A method for reducing the effects of thermal asperities," *IEEE J. Selected Areas Commun*., vol. 19, no. 4, pp. 662 – 667, April 2001.

[4] M. F. Erden and E. M. Kurtas, "Thermal asperity detection and cancellation in perpendicular recording systems," *IEEE Trans. Magn*., vol. 40, no. 3, pp. 1732 – 1737, May 2004.

[5] G. Mathew and I. Tjhia, "Thermal asperity suppression in perpendicular recording channels," *IEEE Trans. Magn*., vol. 41, no. 10, pp. 2878 – 2880, October 2005.

[6] P. Kovintavewat and S. Koonkarnkhai, "Thermal asperity suppression based on least squares fitting in perpendicular magnetic recording systems," *J. of Applied Physics*, vol. 105, no. 7, 07C114, March 2009.

[7] P. Kovintavewat and S. Koonkarnkhai, "Joint TA suppression and turbo equalization for coded partial response channels," to appear in *IEEE Trans. Magn.*, 2010.

[8] S. B. Wicker, *Error control systems for digital communication and storage*. Upper Saddle River, New Jersey: Printice Hall International, 1995.

[9] T. Souvignier, A. Friedmann, M. Oberg, P. Siegel, R. Swanson, and J. Wolf, "Turbo decoding for PR4: parallel vs. serial concatenation," in *Proc. of ICC'99*, vol. 3, pp. 1638-1642, 1999.

[10] R. Gallager, "Low-density parity-check codes," *IRE Trans. on Inform. Theory*, vol. IT-8, pp. 21-28, January 1962.

[11] J. Hagenauer and P. Hoeher, "A Viterbi algorithm with soft-decision outputs and its applications," in *Proc. of Globecom'89*, pp. 1680 – 1686, November 1989.

[12] G. D. Forney, "Maximum-likelihood sequence estimation of digital sequences in the presence of intersymbol interference," *IEEE Trans. Inform. Theory*, vol. IT-18, no. 3, pp. 363 – 378, May 1972.