# Joint TA Suppression and Turbo Equalization for Coded Partial Response Channels

**Article** *in* IEEE Transactions on Magnetics · July 2010

DOI: 10.1109/TMAG.2010.2042572 · Source: IEEE Xplore



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# Joint TA Suppression and Turbo Equalization for Coded Partial Response Channels

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**Thermal asperities (TAs) cause a crucial problem in magnetic recording systems because they can cause a burst of errors in data detection process. Without a TA detection and correction algorithm, the system performance can be unacceptable, depending on how severe the TA effect is. This paper proposes an iterative scheme to suppress the TA effect. This scheme jointly performs TA suppression and turbo equalization on the partial-response channels with error-correction codes. At each turbo iteration, an improved readback signal is obtained by subtracting the reconstructed TA signal from the TA-affected readback signal, where the reconstructed TA signal is computed based on a least-squares fitting technique with an aid of soft decisions from previous turbo iterations. Simulation results indicate that the proposed scheme outperforms the conventional receiver with separate TA suppression and turbo equalization, and is only marginally more complex than the conventional receiver.**

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

## I. Introduction

HIGH-DENSITY magnetic recording systems use the magneto-resistive (MR) read head to sense flux directly via the transitions of the magnetization pattern, resulting in an induced voltage pulse called a transition pulse. Practically, when the slider comes into contact with an asperity (or a surface roughness) on recording media, 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.

Typically, a TA signal has a short rise time (50–160 ns) with a long decay time (1–5 $\mu$s), and its peak TA amplitude could be two to three times the peak of the readback signal [1]. In practice, the TA effect can cause an error burst in data detection process, which could easily exceed the correction capability of the error-correction code (ECC), and thus results in a sector read failure. Consequently, a method to suppress the TA effect is crucial, especially at high recording density.

Several TA detection and correction algorithms have been proposed in the literature [2]–[6] to mitigate the TA effect. In general, 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 of the readback signal. Thus, Klaassen and van Peppen [2] proposed a 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 suitable for a longitudinal recording channel, but not for a perpendicular recording channel because of the d.c. component present in those readback signals. 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 approach to detect and suppress the TA effect. However, this paper focuses on the TA suppression method based on a least-squares (LS) fitting technique [6] because it is simple and robust to changes in the peak TA amplitude, and also performs better than the method presented in [5] as studied in [6].

The large coding gains of iterative ECCs enable reliable communication at very low signal-to-noise ratio (SNR). The iterative decoding technique has also been extended to turbo equalization [7], where the soft-in soft-out (SISO) equalizer and the SISO decoder exchange information so as to improve overall system performance. This means that the TA suppression method must be performed at an SNR lower than ever before. Thus, a conventional receiver, which performs TA suppression and turbo equalization *separately*, normally fails to function properly when the SNR is low enough. To solve this problem, we propose the method for *jointly* performing the tasks of TA suppression and turbo equalization, with complexity comparable to the conventional receiver.

This paper is organized as follows. After explaining the system model in Section II, Section III briefly describes the TA suppression method based on the LS fitting technique [6]. Section IV presents the proposed iterative scheme. Performance comparison will be given in Section V. Eventually, Section VI concludes this paper.

## II. System Description

Consider the coded partial-response (PR) channel model shown in Fig. 1, where $H(D) = \sum_k h_k D^k = 1 + 2D + D^2$ is a PR2 channel. An *i.i.d.* message sequence $x_k \in \{0, 1\}$ is encoded by an error-correction encoder and is mapped to a binary sequence $a_k \in \{\pm 1\}$ with bit period $T$. The readback signal can then be expressed as

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

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

Manuscript received October 27, 2009; revised January 22, 2010; accepted January 30, 2010. Current version published May 19, 2010. Corresponding author: P. Kovintavewat (e-mail: piya@npru.ac.th; pkovintavewat@hotmail.com).

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Digital Object Identifier 10.1109/TMAG.2010.2042572

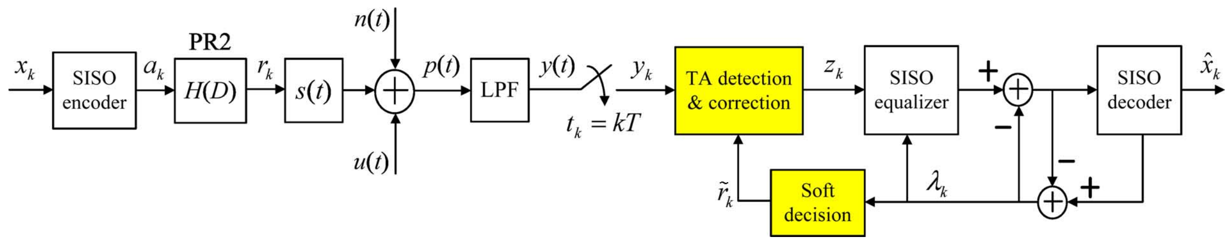


Fig. 1. A channel model with the proposed iterative scheme.

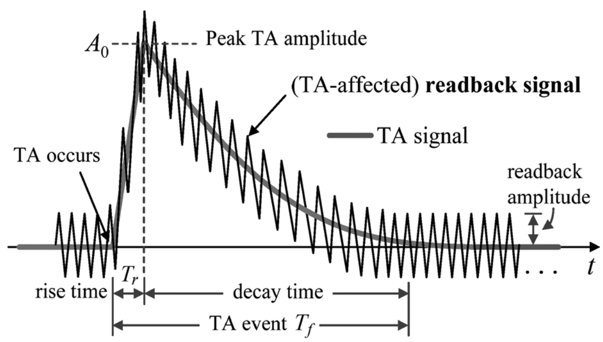


Fig. 2. The TA signal associated with the MR sensor head.

We consider a widely used TA model described by Stupp *et al.* [1] as depicted 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

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

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 $s(t)/T$, to eliminate the 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, $z_k$.

In a conventional setting, the TA detection/correction block is followed by a turbo equalizer, which iteratively exchanges soft information between the SISO equalizer for the PR2 channel and the SISO decoder for the outer code.

## III. Conventional TA Suppression Method

This paper focuses on the TA suppression method based on the LS fitting technique presented in [6] because of its simplicity and robustness to changes in the peak TA amplitude. This 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, $\alpha$ is an integer, and $L = 2\alpha + 1$ is the window length for computing $q_k$. Thus, a TA is detected if $q_k \ge m$, where $m$ is a threshold value.

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 by

$$z_k = \begin{cases} y_k - \hat{u}_k, & \text{if TA is present} \\ y_k, & \text{if TA is absent} \end{cases} \quad (4)$$

where $\hat{u}_k = \hat{u}(kT)$ is the $k$th estimated TA sample. Thus, the conventional receiver sends a sequence $\{z_k\}$ directly to the turbo equalizer, which iterates soft information between the SISO equalizer and the SISO decoder as many iterations as needed.

## IV. Proposed Iterative Scheme

In a conventional receiver, 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, we propose an iterative scheme, where the TA detection/correction block, the SISO equalizer, and the SISO decoder exchange information as depicted in Fig. 1. It will be demonstrated in simulation that the proposed scheme outperforms the conventional receiver as the number of turbo iterations increases. We can now explain how the proposed scheme works as follows.

Denote the first time that the SISO decoder outputs the soft information $\lambda_k$ as the first iteration. It is clear that the proposed scheme performs the same operations as the conventional receiver does at the first iteration. Nevertheless, after the first iteration, the soft information $\lambda_k$ is fed back to both the SISO equalizer and the TA detection/correction block. Accordingly, 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

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

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 $C = \sinh((-\lambda_k + \lambda_{k-1} + \lambda_{k-2})/2)$.

As can be seen in simulation, the performance of the TA suppression method depends strongly on the quality of $\{\tilde{r}_k\}$. In other words, the TA suppression method based on the LS fitting technique will perform best if a sequence $\{c_k\}$ contains only the TA signal and AWGN. 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 the turbo equalizer benefits from better samples $\{z_k\}$, and the TA suppression method benefits from better decisions $\{\tilde{r}_k\}$.

It is apparent that the proposed scheme is essentially a conventional turbo equalizer but with an *extra* TA suppression step added to each iteration. The modified turbo equalizer can help reduce the TA effect as the number of turbo iterations increases. In practice, the complexity of the TA suppression function is generally negligible compared to the equalizer and decoder, so that the overall system is only marginally more complex than a conventional turbo equalizer.

## V. Numerical Result

Consider a rate-8/9 system in which a block of 3640 message bits is encoded by a regular (3, 27) low-density parity-check (LDPC) code [8], resulting in a coded block length of 4095 bits. The parity-check matrix has three 1's in each column and 27 1's in each row. The SISO equalizer is implemented based on the soft-output Viterbi algorithm (SOVA) [9], whereas the SISO decoder is implemented based on the message-passing algorithm [8] with three internal iterations.

In simulation, every 4095-bit data sector is corrupted by one TA signal, which is occurred at the 500th bit with $\beta = 2$, $T_r = 60$ ns, and $T_d = 0.5$ $\mu$s (i.e., a TA event $T_f = 1030T$) [5]. This TA event can be considered as a worst case. We compute the bit-error rate (BER) of the system 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, we employ $L = 51$ to find $\{q_k\}$ and $m = 2.8$ to detect the TA. Note that this threshold $m$ was designed based on the system without ECC at a per-bit SNR, $E_b/N_0$, of 10.7 dB so as to minimize the BER at the output of the SISO equalizer.

Fig. 3 compares the performance of different schemes at the 10th iteration as a function of $E_b/N_0$'s, where the system performance in the absence of TA is referred to as "No TA," and the "Trained" system is the proposed system that has access to all correct decisions (i.e., using $\tilde{r}_k = r_k$). Clearly, without the TA suppression method, the system performance is unacceptable, denoted as "With TA." As illustrated in Fig. 3, the proposed scheme outperforms the conventional receiver, and is about 0.6 dB and 0.8 dB away from the trained system and the system without TA, respectively, at $\mathrm{BER} = 10^{-4}$.

We also compare the performance of the proposed scheme and the conventional receiver by plotting the sector-error rate (SER) as a function of the number of turbo iterations in Fig. 4. It is obvious that the turbo equalization can help increase the performance of the conventional receiver up to 6 iterations, and it then experiences an error floor. On the other hand, the proposed scheme still provides performance improvement as the number of turbo iterations increases. This implies that the quality of the estimated TA signal, $\hat{u}(t)$, obtained from the TA suppression method based on the LS fitting technique and the soft decisions $\{\tilde{r}_k\}$, gets better and better after each iteration. This can be verified by plotting the mean-squared error (MSE) between the actual TA signal $u(t)$ and the estimated TA signal $\hat{u}(t)$, where

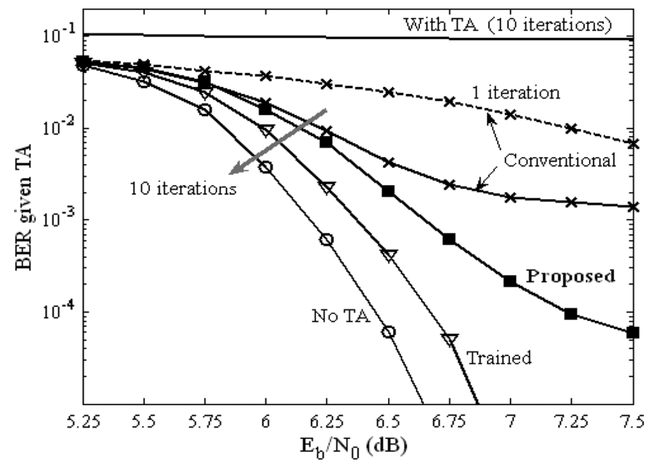


Fig. 3. Performance comparison of different schemes at the 10th iteration.

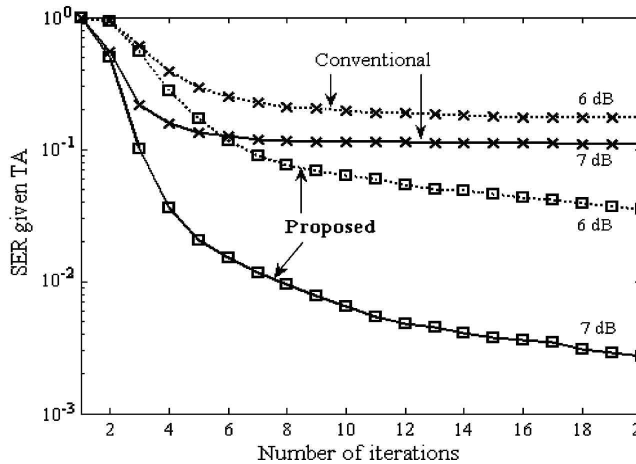


Fig. 4. SER versus the number of turbo iterations.

$$\mathrm{MSE} = 10\log_{10}\left(\frac{1}{T_f}\sum_{k=T_x}^{T_x+T_f}\{u(kT)-\hat{u}(kT)\}^2\right) \quad (6)$$

in decibel (dB), and $T_x$ is the time TA is detected, as depicted in Fig. 5. Clearly, the mismatch between $u(t)$ and $\hat{u}(t)$ decreases as the number of iterations increases. This is why the proposed scheme outperforms the conventional receiver, especially when the number of iterations is large.

Fig. 6 also compares the BER performance of different schemes as a function of peak factors at $E_b/N_0 = 6.65$ dB, where the system without a TA event yields $\mathrm{BER} = 10^{-5}$. It is apparent that without the TA suppression method, the system performance is unacceptable. As shown in Fig. 6, the system performance at the first iteration is constant, which confirms that the TA suppression method based on the LS fitting technique is robust to changes in the peak TA amplitude [6]. Although the BER performance of different schemes is high, this is because the TA event used in the simulation is severe

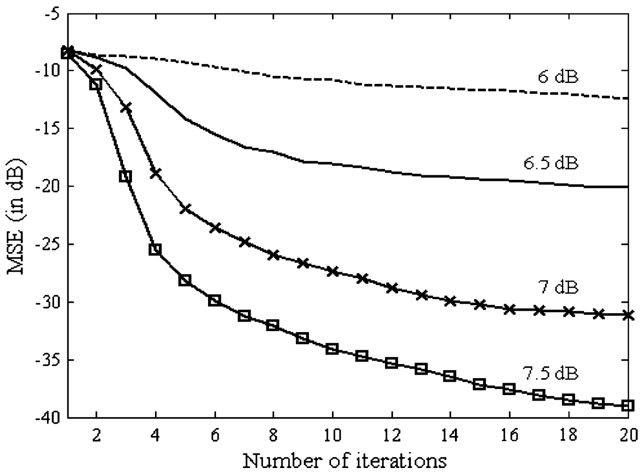


Fig. 5. The MSE of the proposed scheme at different $E_b/N_0$'s.

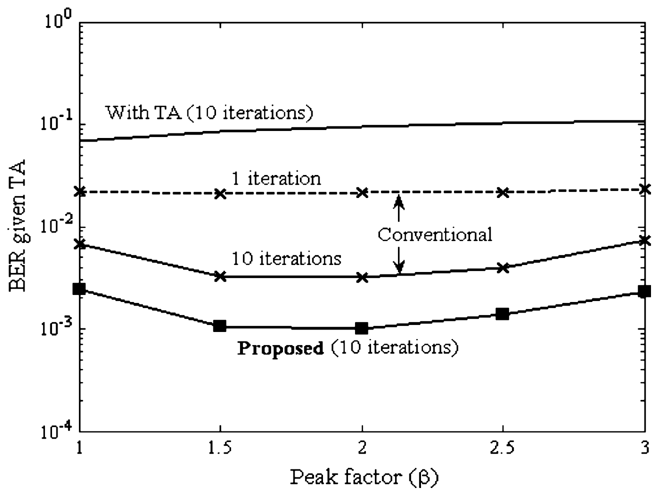


Fig. 6. BER performance with different peak factors.

(i.e., all data sectors contain one TA event with a large peak TA amplitude and a long decay time). However, the proposed scheme still performs better than the conventional receiver for all peak TA amplitudes.

Furthermore, by using the LS fitting technique to estimate the TA signal, we can further reduce the complexity of the proposed scheme, while maintaining satisfactory BER performance, as suggested in [6]. It is important to note that because most hard drives currently use tunneling MR heads, the TA response no longer looks like the one shown in Fig. 2 [10]. Therefore, other TA suppression methods must be employed to estimate this new TA signal. Nevertheless, it should be pointed out that any TA suppression method that exploits the soft decisions obtained from the turbo equalizer can still be utilized in the proposed iterative scheme so as to obtain the performance improvement if compared to the conventional receiver.

## VI. Conclusion

The TA effect can distort the readback signal to the extent of causing a sector read failure. It is clear that the conventional receiver, which performs TA suppression and turbo equalization separately, cannot work properly when the SNR is low. This paper proposes an iterative scheme to jointly perform TA suppression and turbo equalization for coded partial-response channels. At each turbo iteration, the proposed scheme uses soft decisions from the SISO decoder to improve the performance of the TA suppression method so as to obtain an improved readback signal, which in turn improves the performance of the turbo equalizer in the next iteration.

Simulation results have shown that the proposed scheme outperforms the conventional receiver, especially when the number of turbo iterations is large, and is only marginally more complex than the conventional receiver.

## Acknowledgment

This project was supported in part by the Industry/University Cooperative Research Center (I/UCRC) in HDD Component, the Faculty of Engineering, Khon Kaen University, under Grant CPN-R&D 01-23-52 EF, and in part by the National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA), Thailand.

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