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Original Article

A method for thermal asperity suppression in perpendicular recording channels

Piya Kovintavewat*¹ and Santi Koonkarnkha²

¹ Data Storage Technology Research Unit, Nakhon Pathom Rajabhat University,
Mueang, Nakhon Pathom, 73000 Thailand.

² Department of Electrical Engineering, King Mongkut's University of Technology North Bangkok,
Bang Sue, Bangkok, 10800 Thailand.

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Abstract

A novel method for reducing the effect of a thermal asperity (TA) in perpendicular recording channels is proposed, which consists of two channels running in parallel, one for the $H(D)$ target and the other for the $G(D)H(D)$ target equipped with a bandpass filter $G(D) = 1 - D^2$. The Viterbi detector (VD) in the $H(D)$ channel has a lower bit-error rate (BER) in the absence of a TA, whereas that in the $G(D)H(D)$ channel has a lower BER in the presence of a TA. Therefore, the overall decoded bit stream is selected from these two VDs, depending on whether a TA is detected. Because the noise after $G(D)$ filtering is correlated, we also propose a noise predictor filter of the form $P(D) = -0.5D^2$ to whiten this correlated noise in a per-survivor manner. Experimental results indicate that the proposed TA suppression method outperforms the existing methods for all peak TA amplitudes.

Keywords: bandpass filter, noise predictor filter, perpendicular recording, thermal asperity, thermal asperity detection and correction method

1. Introduction

To achieve very high recording densities, magneto-resistive (MR) read heads have been employed in magnetic recording systems instead of the inductive heads. Practically, the MR read head senses the change in 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) in the readback signal.

A typical TA signal has a short rise time (60-150 ns) with a long decay time (1-5 ms), and its peak TA amplitude

can be 2 to 3 times the peak of the readback signal (Stupp *et al.*, 1999; Dorfman and Wolf, 2001). If precautions are not carefully taken, the TA effect can cause severe transient noise, off-track perturbation, or even loss of timing synchronization, which then results in a burst of errors in data detection process. Practically, this error burst could easily exceed the correction capability of the error-control code (ECC), and thus results in a sector read failure. Therefore, a method to mitigate the TA effect is crucial, especially at high recording densities.

Many TA suppression methods have been proposed in the literature to reduce the TA effect. In practice, the TA causes a shift in the baseline of the readback signal. The average value of the normal readback signal is zero, whereas that of the TA-affected readback signal is not. Thus, Klaassen and van Peppen (1997) proposed TA detection by looking at the baseline of the averaged readback signal, while the TA correction was performed by use of a high-pass filter. Dorfman and Wolf (2001) proposed a method to combat the

* Corresponding author.
Email address: piya@npru.ac.th

TA effect by passing the TA-affected readback signal through a filter $(1 - D)$, where D is a delay operator. This method has been tested with an EPR4 target in longitudinal recording channels, where the number of bits corrupted by the TA effect is dramatically reduced. Nonetheless, this method is not suitable for a perpendicular recording channel because this channel contains a d.c. component. For perpendicular recording channels, Erden and Kurtas (2004) proposed a TA detection and correction method by using different low-pass and high-pass filters, while Mathew and Tjhia (2005) proposed a simple threshold-based approach to detect and suppress the TA effect. Finally, Kovintavewat and Koonkarnkhai (2009) proposed a simple TA suppression method based on a least-squares fitting technique in perpendicular recording channels.

This paper proposes a new TA suppression method to alleviate the TA effect in perpendicular recording channels. The proposed method consists of two channels running in parallel, one for the $H(D)$ target, and the other for the $G(D)H(D)$ target equipped with a bandpass filter $G(D)$. Practically, the Viterbi detector (VD) (Forney, 1972) in the $H(D)$ channel has a lower BER in the absence of a TA, whereas that in the $G(D)H(D)$ channel has a lower BER in the presence of a TA. Thus, the overall decoded bit stream is selected from these two VDs, depending on whether a TA is detected. In general, it is well-known that the VD is an *optimum* detector if the noise component at the input of the VD is *white* noise (Forney, 1972). However, because the noise after $G(D)$ filtering is correlated, we then propose to embed a noise predictor filter (Chevillat *et al.*, 1992) inside the VD so as to whiten this correlated noise. The resulting VD is denoted as “the modified VD.” In addition, to reduce the complexity of the modified VD, we also propose to perform noise whitening in a per-survivor fashion (Raheli *et al.*, 1995).

This paper is organized as follows. After describing a channel model in Section 2, Section 3 briefly explains a widely used TA model. Section 4 presents the proposed TA suppression method. Simulation results are given in Section 5. Finally, Section 6 concludes this paper.

2. Channel Model

Consider a coded EPR2 (Kovintavewat *et al.*, 2002) channel model in Figure 1, where a message sequence $x_k \in$

$\{0, 1\}$ is encoded by an ECC encoder and is mapped to a coded sequence $a_k \in \{\pm 1\}$. The coded sequence a_k with a bit period T is filtered by an EPR2 channel represented by $H(D) = \sum_k h_k D^k = 1 + 3D + 3D^2 + D^3$. The TA-affected readback signal can then be written as

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

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

At the receiver, the readback signal $p(t)$ is filtered by an ideal low-pass filter (LPF), whose impulse response is $s(t)/T$, and is then sampled at a symbol rate of 500 Mbps (Mathew and Tjhia, 2005), assuming perfect synchronization. The sampler output, y_k , is fed to the TA detection and correction block, followed by the VD and the ECC decoder.

3. Thermal Asperity Model

We consider a widely used TA model described by (Stupp *et al.*, 1999) as illustrated in Figure 2 because it fits captured spin stand data and drive data very well (Erden and Kurtas, 2004). Typically, the TA signal associated with MR sensors has a short rise time with a long decay time, and its effect is assumed to decay exponentially, which can be modeled as (Mathew and Tjhia, 2005)

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

where $A_0 = \beta \sum_k |h_k|$ is the peak TA amplitude, $\beta > 0$ is a 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 $T_f = T_r + 4T_d$ (Mathew and Tjhia, 2005), 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.

It should be noted that if the amplitude of the TA signal exceeds a certain limit (usually 3-5 times the peak of the readback signal), the TA-affected readback signal will exceed (saturate) the upper limit of preamplifier, filters, or analog-to-digital converter (ADC). When this occurs, it might cause an

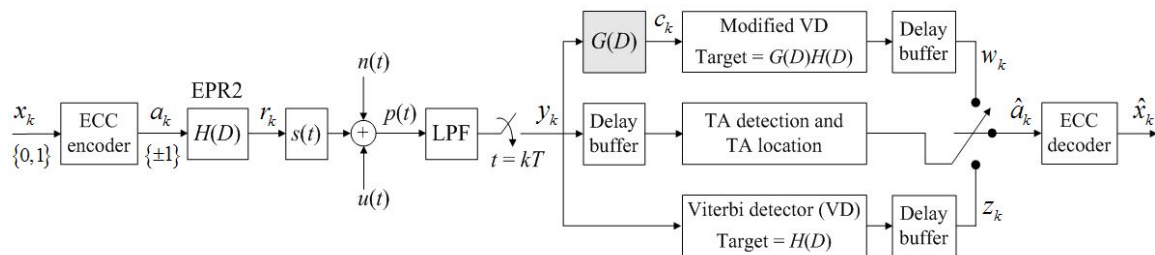


Figure 1. A coded EPR2 channel model with the proposed TA suppression method.

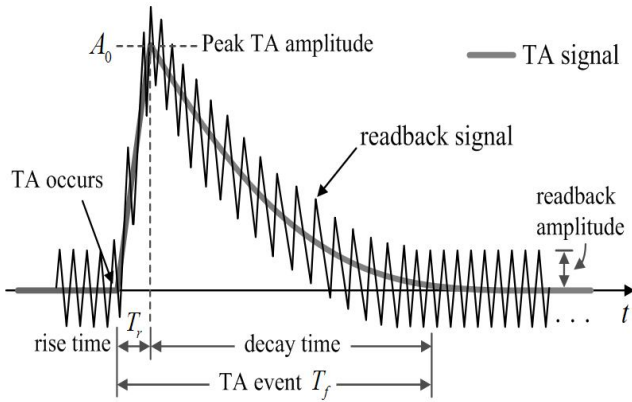


Figure 2. A widely used TA signal, $u(t)$.

error burst in data detection process because the VD will not be able to decode reliably. In addition, even if a TA amplitude is relatively small (e.g., less than three times the peak of the readback signal), the VD may still output some errors because of the change in the baseline shift. Nonetheless, in this paper, we will not take into account preamp saturation limit and ADC quantization effects.

4. Proposed TA Suppression Method

This paper proposes a new TA suppression method as shown in Figure 1, whose structure is similar to the method proposed in (Dorfman and Wolf, 2001). Specifically, the proposed method employs two VDs running in parallel. One channel is matched to the $H(D)$ target, whereas the other is matched to the $G(D)H(D)$ target equipped with a bandpass filter $G(D)$. Because the perpendicular recording channels have significant low-frequency content, we propose a bandpass filter of the form $G(D) = (1 - D^2)$ to eliminate a TA (Koonkarnkhai *et al.*, 2010), while maintaining most energy of the readback signal. Since the noise component after $G(D)$ filtering is correlated, we employ the *modified* VD, i.e., the VD equipped with a noise predictor filter $P(D)$, to combat this correlated noise.

Practically, the VD in the $H(D)$ channel has a lower BER when a TA is absent, whereas the modified VD in the $(1 - D^2)H(D)$ channel has a lower BER when a TA is present. Thus, the overall decoded bit stream is chosen from the outputs of these two VDs. If a TA is detected, a decoded bit w_k is selected; otherwise, a decoded bit z_k is selected (see Figure 1).

To detect a TA, we first pass a sequence $\{y_k\}$ through a digital low-pass filter to smoothen the readback signal, whose transfer function is given by (Erden and Kurtas, 2004)

$$F(D) = \frac{1}{m - (m-1)D}, \quad (3)$$

where m determines the cutoff frequency. Next, we compute the average value of the readback signal, q_k , according to

$$q_k = q(kT) = \frac{1}{L_1 + L_2 + 1} \sum_{i=k-L_1}^{k+L_2} b_i, \quad (4)$$

where L_1 and L_2 are integers, and b_i is the i -th sample of the readback signal after filtering by an $F(D)$. Therefore, a TA is detected if $q_k \geq m_1$, where m_1 is a threshold value. It can be shown that a large threshold will lead to a better AWGN performance at the expense of the TA performance. On the other hand, a small threshold might lead to many false alarms, resulting in the output bits being $\{w_k\}$ in the absence of a TA.

Based on extensive simulation search, we found that $m = 220$, $L_1 = 10$, $L_2 = 80$, and $m_1 = 1$ are suitable parameters for this EPR2 channel because they can provide a good performance both in the presence and in the absence of TAs.

4.1 Noise predictor filter

From Figure 1, the noise component after the sampler, n_k , is *i.i.d.* zero-mean Gaussian random variable with variance $\sigma^2 = N_0/(2T)$. Clearly, the noise after $G(D) = 1 - D^2$ filtering is the colored noise, $w_k = n_k - n_{k-2}$. In general, the total noise power can be reduced by noise prediction.

Let $P(D) = \sum_{i=1}^L p_i D^i$ denote a noise predictor filter, where L is a predictor order, and p_i is the i -th coefficient of $P(D)$. Then, the signal

$$e_k = w_k - \hat{w}_k = w_k - \sum_{i=1}^L p_i w_{k-i}, \quad (5)$$

represents the prediction error (or, equivalently, the whitened noise), where \hat{w}_k is an estimate of w_k .

The coefficients of $P(D)$ can be obtained by minimizing the mean-squared error (MSE) between w_k and \hat{w}_k , i.e.,

$$E[e_k^2] = E[(w_k - \hat{w}_k)^2] = E\left[\left(w_k - \sum_{i=1}^L p_i w_{k-i}\right)^2\right], \quad (6)$$

where $E[\cdot]$ is an expectation operator. By taking the derivative of Equation 6 with respect to p_i , and setting the result to zero, one obtains

$$R_w(j) = \sum_{i=1}^L p_i R_w(j-i), \quad (7)$$

for $j = 1, 2, \dots, L$, where $R_w(j)$ is the autocorrelation function of w_k . For the bandpass filter of the form $G(D) = (1 - D^2)$, it can be shown that the autocorrelation function $R_w(j)$ is given by

$$R_w(j) = 2R_n(j) - R_n(j-2) - R_n(j+2), \quad (8)$$

where

$$R_n(j) = \begin{cases} \sigma_n^2, & j = 0 \\ 0, & j \neq 0 \end{cases}, \quad (9)$$

is the autocorrelation function of n_k . Accordingly, for $L = 2$, we obtain $P(D) = -0.5D^2$, which is the proposed noise predictor filter that is used in the modified VD.

4.2 Modified viterbi detector

The proposed TA suppression method employs the modified VD because the noise component at the input of the VD, w_k , is correlated. The key idea is to include the noise predictor filter $P(D)$ in the branch metric calculation of the VD. Denote (u, v) as the transition from state u to state v in the trellis diagram (Forney, 1972). Thus, the modified VD computes the branch metric at time k for the transition from state u to state v , i.e., $\rho_k(u, v)$, according to (Chevillat *et al.*, 1992)

$$\rho_k(u, v) = |c_k - \hat{r}_k(u, v) - \hat{w}_k(u, v)|^2, \tag{10}$$

where c_k is the k -th sample at the input of the modified VD, $\hat{r}_k(u, v)$ is the noiseless channel output associated with a transition (u, v) , and $\hat{w}_k(u, v)$ is the predicted noise sample associated with a transition (u, v) , which is obtained by

$$\hat{w}_k(u, v) = \sum_{i=1}^L p_i \{c_{k-i} - \hat{r}_{k-i}(u, v)\}. \tag{11}$$

Generally, we need to keep track of the predicted noise sample $\hat{w}_k(u, v)$ of each transition, which then requires trellis expansion (Chevillat *et al.*, 1992). However, to reduce its complexity, we compute the predicted noise $\hat{w}_k(u, v)$ based on tentative decisions associated with each survivor path (Raheli *et al.*, 1995), thus requiring no trellis expansion.

5. Numerical Results

In simulation, each data sector is corrupted by one TA signal, which occurs at the 1000-th bit with $\beta = 2$, $T_r = 60$ ns, and $T_d = 0.5 \mu s$ (i.e., a TA event $T_f = 1030T$). This TA event can be considered as the worst case. We compute the BER of the system based on a minimum number of 1000 data sectors and 500 erroneous bits, and call that number as “BER given TA.” In this paper, the proposed TA suppression method is compared with the methods presented in (Dorfman and Wolf, 2001; Mathew and Tjhia, 2005), where the method presented in Dorfman and Wolf (2001) is denoted as “Method 1,” and the one presented in Mathew and Tjhia (2005) is referred to as “Method 2.”

First, we investigate the performance of different TA suppression methods in an *uncoded* system (i.e., the system without ECC) as depicted in Figure 1. The *per-bit* signal-to-noise ratio (SNR) is defined as

$$\frac{E_b}{N_0} = 10 \log_{10} \left(\frac{\sum_k |h_k|^2}{2\sigma^2} \right) \tag{12}$$

in decibel (dB). Figure 3 compares the BER performance of different schemes as a function of E_b/N_0 's, where the system performance in the absence of a TA is denoted as “No TA.” It is clear that without the TA suppression method (denoted

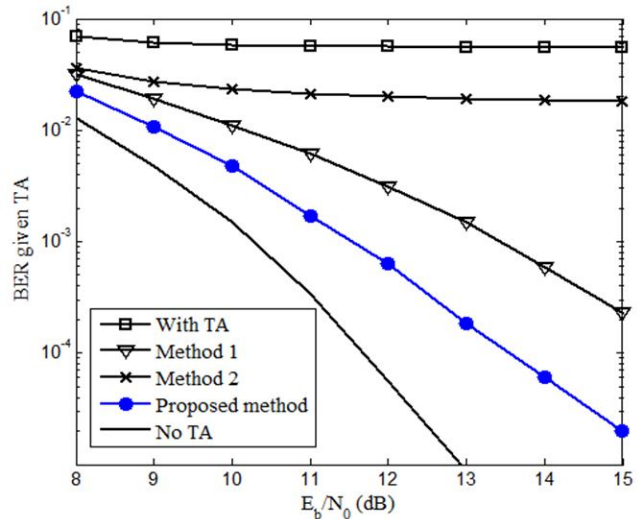


Figure 3. BER performance of different methods in uncoded systems.

as “With TA”), the system performance is unacceptable. As illustrated in Figure 3, the proposed method performs better than other methods. We also compare the BER performance of different schemes as a function of peak-factors in Figure 4 at $E_b/N_0 = 11.6$ dB, where the system without a TA event yields $BER \approx 10^{-4}$. Obviously, the proposed method still performs better than other methods for all peak-factors, and is robust to changes in the peak-factors (or, equivalently, the peak TA amplitudes).

To demonstrate that the TA effect can deteriorate the overall system performance even with ECC, we investigate the performance of different TA suppression methods in

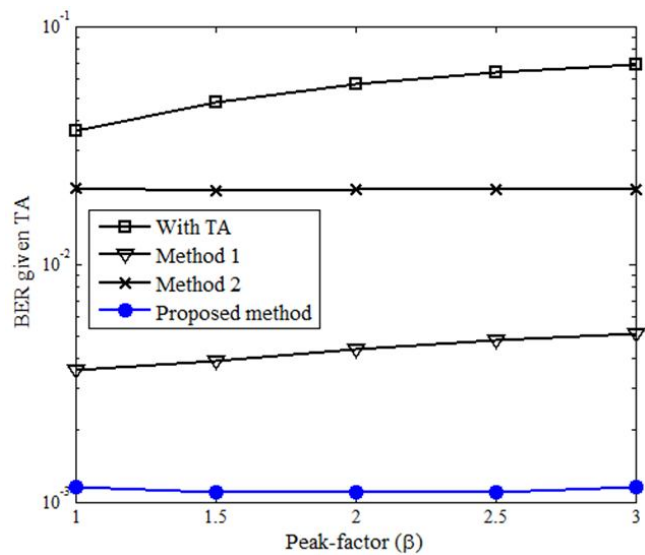


Figure 4. BER performance with different peak-factors in uncoded systems.

coded systems (i.e., the system with ECC). We consider a rate-223/255 coded EPR2 system in which a block of 3568 message bits, $\{x_k\}$, is encoded by a (223, 255) Reed-Solomon (RS) code (Cheng and Siegel, 2004), resulting in a coded block length of 4080 bits, $\{a_k\}$. Then, the detected bits $\{\hat{a}_k\}$ in Figure 1 are decoded by the same RS code to obtain an estimated message sequence $\{\hat{x}_k\}$. To account for a code rate, the SNR used in a simulation of coded systems is defined as

$$\frac{E_c}{N_0} = \frac{E_b}{N_0} R \tag{13}$$

in dB, where $R = 223/255$ is a code rate for this simulation setup.

Figure 5 compares the BER performance of different schemes in coded systems as a function of E_c/N_0 's. In general, the BER performance of the coded system is much better than that of the uncoded system, especially at high SNR, because the RS code can correct the error bursts. As depicted in Figure 5, without efficient TA suppression methods, the BER performance is unacceptable even in coded systems. This implies that the ECC cannot help correct the errors caused by the TA effect. Nevertheless, the proposed method still outperforms the existing methods in coded systems. Specifically, a 1.5 dB gain at $BER \approx 10^{-4}$ can be obtained from the proposed method if compared to Method 1. Finally, we also compare the performance of different schemes as a function of peak-factors in Figure 6. Apparently, the proposed method yields better performance than the existing methods for all peak-factors. This can be implied that the proposed method is more robust than the others.

6. Conclusion

The TA effect can distort the readback signal to such an extent that it can cause a sector read failure, even in the presence of powerful error-control codes. This paper proposes a novel TA suppression method to reduce the TA effect in perpendicular recording channels. The proposed method consists of two channels running in parallel, one for the $H(D)$ target, and the other for the $G(D)H(D)$ target equipped with a bandpass filter $G(D) = 1 - D^2$ to suppress the TA effect. Because the noise after $G(D)$ filtering is correlated, we also proposed to embed a noise predictor filter of the form $P(D) = -0.5D^2$ inside the Viterbi detector to whiten this correlated noise in a per-survivor manner. Simulation results have shown that the proposed TA suppression method outperforms the existing methods for all peak TA amplitudes.

Eventually, it is important to note that the proposed method might not be suitable for the hard drive that employs the tunneling MR heads because the TA response no longer looks like the classical TA model shown in Figure 2 (Ohashi *et al.*, 2001). Thus, other techniques should be considered for such a hard drive (Gill, 2001).

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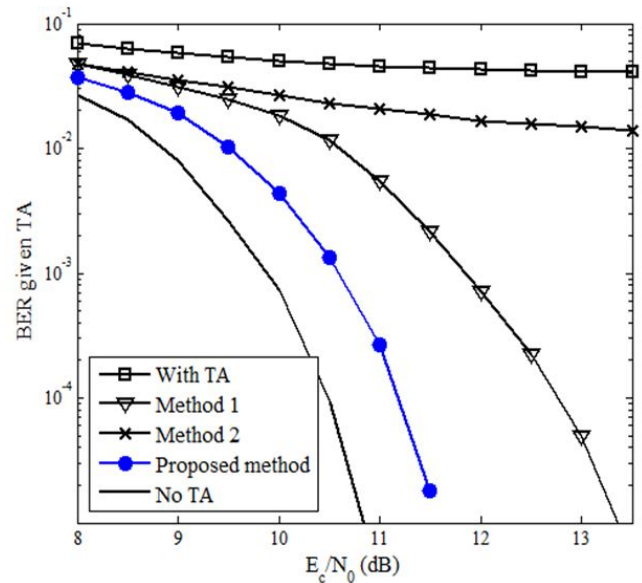


Figure 5. BER performance in coded systems.

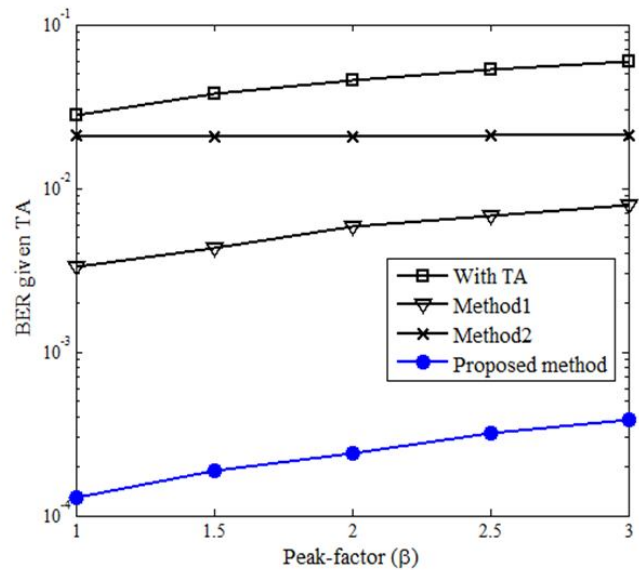


Figure 6. BER performance with different peak-factors in coded systems.

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