ROBUSTNESS OF PER-SURVIVOR ITERATIVE TIMING RECOVERY AGAINST THERMAL ASPERITY IN PERPENDICULAR RECORDING CHANNELS

Piya Kovintavewat

Faculty of Science and Technology, Nakhon Pathom Rajabhat University
85 Malaiman rd., Muang district, Nakhon Pathom 73000, Thailand
piya@npru.ac.th

ABSTRACT

Thermal asperity (TA) causes a major problem in magnetic recording systems. Without the TA detection and correction algorithm, the system performance (even with perfect synchronization) can be unacceptable, depending on how severe the TA effect is. In this paper, we investigate the robustness of different timing recovery schemes in the presence of TA. Simulation results indicate that per-survivor iterative timing recovery provides satisfactory system performance when used in conjunction with the TA detection and correction algorithm.

1. INTRODUCTION

Timing recovery is a crucial component in magnetic recording systems. It is the process of synchronizing the sampler with the received analog signal. Sampling at wrong times can have a dominant impact on overall performance. Many factors directly affect the performance of timing recovery, including the channel characteristics, nonlinearities, distortions, noise, and so forth. One of the distortions that has a great impact on the functionality of timing recovery is *thermal asperity* (TA).

During read process, the magnetoresistive (MR) head senses the change in flux via the transitions of the magnetic pattern written on the disk surface, resulting in an induced voltage 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 extra voltage transient known as TA. The vulnerability of MR sensors to TA was identified shortly after their discovery [1].

The TA causes a major problem in data detection process because it easily affects timing recovery to lose synchronization. In other words, the TA effect will increase the probability of occurrence of a cycle slip [2]. The system performance (even with perfect synchronization) can be unacceptable, depending on how severe the TA effect is. We observed that without the TA detection and correction algorithm, no timing recovery scheme performs well in the presence of severe TA.

Several TA detection and correction algorithms have been proposed in the literature [4] to reduce the TA effect. After applying any of these algorithms, there might be some residual TA effects left in a system. In this paper, we investigate the robustness of different timing recovery schemes in the presence of TA after applying the TA detection and correction algorithm.

This paper is organized as follows. After describing our channel model in Section 2, we summarize how per-survivor iterative timing recovery performs in Section 3. Section 4 explains how to model the TA signal. Simulation results are given in Section 5. Finally, Section 6 concludes this paper.

This paper was partly presented at IEEE international conference on magnetics (INTERMAG 2005), Nagoya, Japan, April 4 - 8, 2005 [3].

2. CHANNEL DESCRIPTION

We consider the coded channel model shown in Fig. 1. A message sequence $x_k \in \{0,1\}$ is encoded by an error-correction encoder and is mapped to a coded sequence $a_k \in \{\pm1\}$. The coded sequence a_k with bit period T is filtered by $(1-D)/2$, where D is the delay operator, to form a transition sequence $b_k \in \{-1,0,1\}$, where $b_k = \pm1$ corresponds to a positive or a negative transition, and $b_k = 0$ corresponds to the absence of a transition. The transition sequence b_k passes through a perpendicular recording channel whose transition response is given by $g(t) = \mathrm{erf}(2t\sqrt{\ln 2}/\mathrm{PW}_{50})$ [5], where $\mathrm{erf}(\cdot)$ is an error function and PW_{50} determines the width of the derivative of $g(t)$ at half its maximum. In the context of magnetic recording, a *normalized recording density* is defined as $\mathrm{ND} = \mathrm{PW}_{50}/T$, which determines how many data bits can be packed within the resolution unit PW_{50}.

The read-back signal, $p(t)$, can then be expressed as [3]

$$\begin{aligned} p(t) &= \sum_k a_k\{g(t-kT-\Delta t_k-\tau_k) \\ &\quad -g(t-(k+1)T-\Delta t_{k+1}-\tau_k)\} + n(t), \quad (1) \end{aligned}$$

where $n(t)$ is additive white Gaussian noise with two-sided power spectral density $N_0/2$. The media jitter noise, Δt_k, is modeled as a random shift in the *transition position* with a

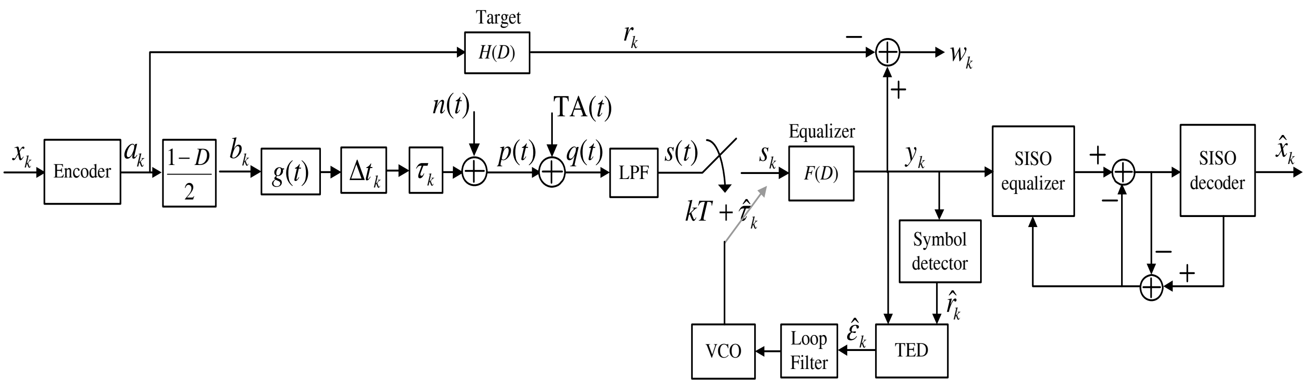

Figure 1: Channel model with target design.

Gaussian probability distribution function with zero mean and variance $|b_k|\sigma_j^2$ (i.e., $\Delta t_k \sim \mathcal{N}(0, |b_k|\sigma_j^2)$) truncated to $T/2$, where $|x|$ takes the absolute value of x. The clock jitter noise, τ_k, is modeled as a random walk [5] according to $\tau_{k+1} = \tau_k + \mathcal{N}(0, \sigma_w^2)$, where σ_w determines the severity of the timing jitter. Then, the read-back signal $p(t)$ is corrupted by the TA signal, TA(t).

At the receiver, the signal $q(t)$ is filtered by a seventh-order Butterworth low-pass filter (LPF), whose cutoff frequency is at $1/(2T)$, and is sampled at time $kT + \hat{\tau}_k$, where $\hat{\tau}_k$ is the receiver's estimate of τ_k. The sampler output s_k is equalized by an equalizer, $F(D)$, such that an equalizer output y_k closely resembles a desired sample, r_k. Note that the design of a target and its corresponding equalizer can be found in [6].

Conventional timing recovery is based on a phase-locked-loop (PLL) [2], consisting of a timing error detector (TED), a loop filter, and a voltage-controlled oscillator (VCO). A decision-directed TED [2] is used to compute the receiver's estimate of the timing error $\epsilon_k = \tau_k - \hat{\tau}_k$ based on the Mueller and Müller (M&M) TED algorithm [7] according to $\hat{\epsilon}_k = \{y_k \hat{r}_{k-1} - y_{k-1}\hat{r}_k\}$, where $\hat{r}_k$ is an estimate of r_k produced by the Viterbi detector [8] with a decision delay of $4T$. The next sampling phase offset is updated by a second-order PLL by [2]

$$\hat{\theta}_{k+1} = \hat{\theta}_k + \beta\hat{\epsilon}_k, \quad (2)$$

$$\hat{\tau}_{k+1} = \hat{\tau}_k + \alpha\hat{\epsilon}_k + \hat{\theta}_{k+1}, \quad (3)$$

where $\hat{\theta}_k$ represents an estimate of frequency error, and α and β are the PLL gain parameters.

In the conventional receiver, conventional timing recovery is followed by a turbo equalizer [9] (see Fig. 1), which iteratively exchanges soft information between a soft-in soft-out (SISO) equalizer and an SISO decoder.

3. PER-SURVIVOR ITERATIVE TIMING RECOVERY

Per-survivor iterative timing recovery was first proposed by Kovintavewat, Barry, Erden, and Kurtas [5] to deal with the problem of timing recovery operating at low signal-to-noise ratio (SNR). This scheme jointly performs timing recovery, equalization, and error-correction decoding. Although it outperforms other iterative timing recovery schemes in the absence of TA, it has very high complexity. To solve this problem, a reduced-complexity per-survivor iterative timing recovery scheme has been proposed in [10]. It is realized by first applying the per-survivor processing (PSP) concept [11] to a soft-output Viterbi algorithm (SOVA) [12], resulting in a per-survivor SOVA equalizer, denoted as "PSP-SOVA" [10]. Then, reduced-complexity per-survivor iterative timing recovery iteratively exchanges soft information between PSP-SOVA and the SISO decoder.

In this paper, we will focus only on reduced-complexity per-survivor iterative timing recovery and will refer to it as *per-survivor iterative timing recovery*. Hence, we compare its performance with other iterative timing recovery schemes in the presence of TA.

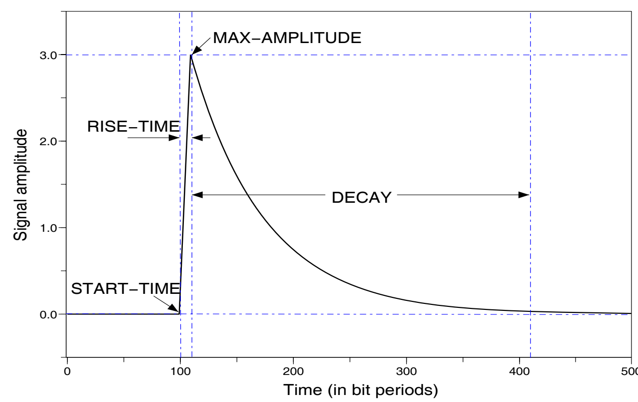

Figure 2: TA signal, TA(t).

4. THERMAL ASPERITY MODELING

This section briefly describes how to generate the TA signal, TA(t). We use the TA model described by Stupp *et al* [13] as depicted in Fig. 2 because it fits captured spin stand data

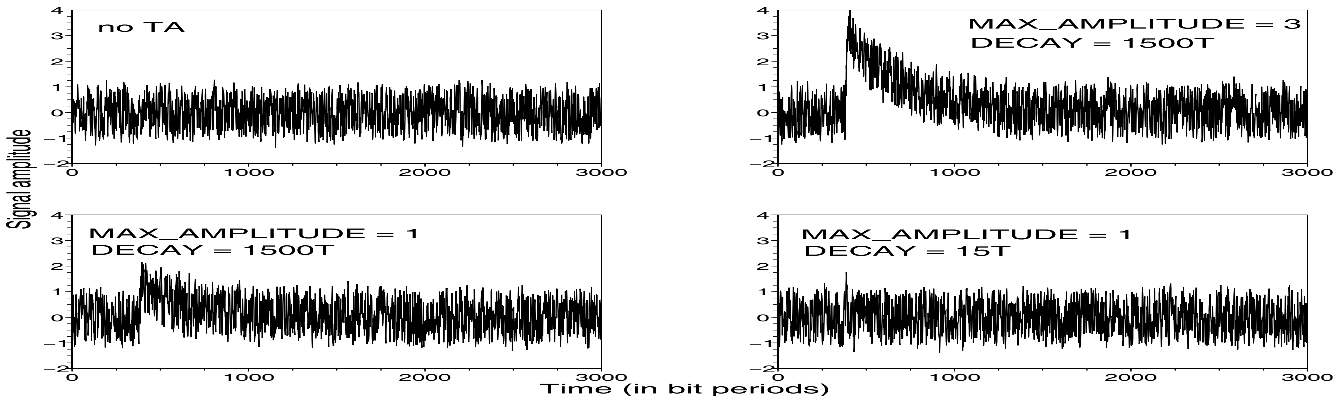

Figure 3: An example of the read-back signal at the input of an LPF with different TA effects

and drive data very well [4]. As shown in Fig. 2, this TA model is specified by four parameters as follows:

- START-TIME: It indicates where the TA effect starts.
- RISE-TIME: It specifies the time required for the TA signal to rise from 0 to its maximum amplitude (defined by MAX-AMPLITUDE).
- MAX-AMPLITUDE: It sets the maximum amplitude of the TA signal.
- DECAY: The TA effect is assumed to decay exponentially, and this parameter specifies the time required for TA(t) to decay from its maximum amplitude to 0.01.

Based on this model, we can model several TA scenarios that typify the conditions observed in product testing. For example, Fig. 3 shows the read-back signal with different TA effects at the input of an LPF, where START-TIME = $400T$ and RISE-TIME = $10T$. Clearly, immediately after the slider comes into contact with an asperity, the transient TA effect quickly and significantly changes the baseline of the read-back signal. Then, the slider and the asperity cool down so that the baseline of the signal decays to its original level. As depicted in Fig. 3, one would expect that the larger the values of MAX-AMPLITUDE and DECAY, the worse the system performance, as will be seen in the next section.

5. NUMERICAL RESULTS

We consider a perpendicular recording channel with ND = 2, $\sigma_j/T = 3\%$ media jitter noise, $\sigma_w/T = 0.5\%$ clock jitter noise, and 0.2% frequency offset. The 3-tap target and a 21-tap equalizer were designed at the SNR required to achieve BER $= 10^{-5}$. The 3-tap target is $H(D) = 1 + 1.15D + 0.48D^2$. The SNR is defined as

$$\mathrm{SNR} = 10 \log_{10}\left(\frac{E_i}{N_0}\right) \text{ (in dB)}, \tag{4}$$

where E_i is the energy of the channel impulse response (the derivative of the transition response scaled by 2). The PLL gain parameters were designed to recover phase/frequency changes within 100 bit periods during acquisition mode and 256 bit periods during tracking mode, based on a linearized

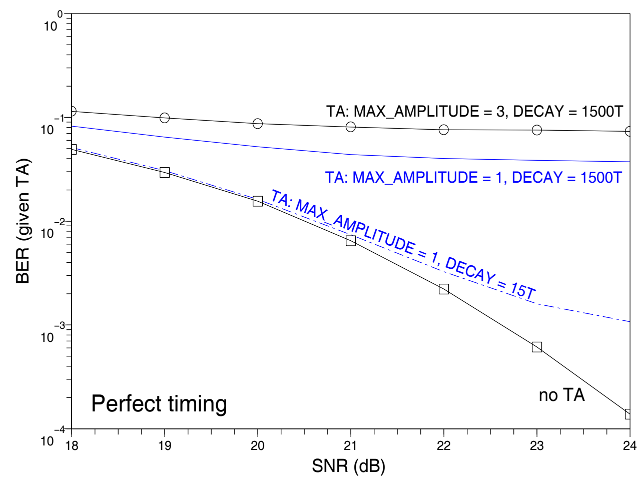

Figure 4: BER performance of the (uncoded) system with perfect timing

model of PLL [2]. Note that a 100-bit preamble will be *inserted* to a sequence a_k before passing it through the channel. At the receiver, after performing timing recovery, the preamble will be *discarded* at the equalizer output before feeding the resulting sequence to the turbo equalizer.

We first show how TA affects the system performance. To do so, we consider an *uncoded* system (i.e., a system without error-correction codes (ECCs)). In other words, we measure the system performance directly at the output of the SISO equalizer, which is implemented based on SOVA with a decoding depth of $15T$. Fig. 4 plots the bit-error rate (BER) performance of the system with *perfect timing*[1] for different TA effects. Clearly, when the TA effect is severe (e.g., when DECAY = $1500T$ and MAX-AMPLITUDE $\geq$ 1), the system performance is unacceptable. However, the system performance seems to be acceptable when MAX-AMPLITUDE = 1 and DECAY = $15T$. This explains why

[1] It is the conventional receiver that knows exactly where to sample the received analog signal.

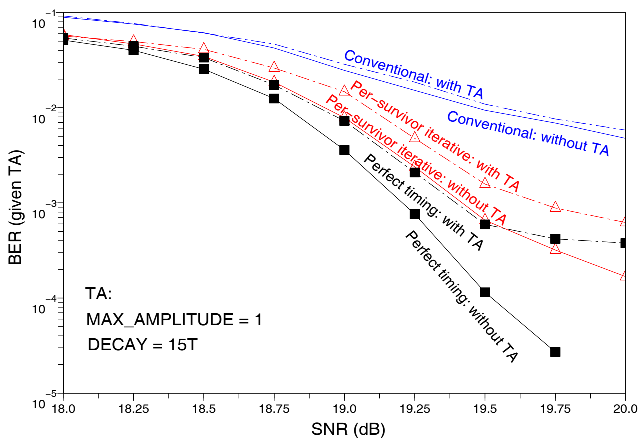

Figure 5: Performance comparison for a coded system at the 5-th iteration.

the TA detection and correction algorithm [4] is needed so as to reduce the TA effect. Therefore, from now on, we will assume that after applying the TA detection and correction algorithm, the TA effect reduces to MAX-AMPLITUDE = 1 and DECAY = $15T$.

Next, we consider a rate-8/9 *coded* system in which a block of 3640 message bits, $\{x_k\}$, is encoded by a regular $(3, 27)$ low-density parity-check (LDPC) code [14], resulting in a coded block length of 4095 bits, $\{a_k\}$. The parity-check matrix has 3 ones in each column and 27 ones in each row. The SISO decoder is implemented based on the message passing algorithm [14] with 5 internal iterations. To account for a coded system, we define a *user density*, D_u, as $D_u =$ ND/code rate. Furthermore, we assume that there is no frequency offset left in the system after the first iteration. This means that a first-order PLL will be used after the first iteration. Each BER point was computed many data packets as needed until at least 100 packets in error were collected at the 5-th iteration.

Fig. 5 compares the performance of different iterative timing recovery schemes for $D_u = 2$. It is apparent that per-survivor iterative timing recovery outperforms the conventional receiver. This implies that per-survivor iterative timing recovery is more robust against TA than the conventional receiver. This is because it can automatically correct a cycle slip [5, 10], as opposed to the conventional receiver.

6. CONCLUSION

We investigated the performance of different timing recovery schemes in the presence of TA. Without the TA detection and correction algorithm, no timing recovery scheme works when TA is severe. After applying the TA detection and correction algorithm, we have shown that per-survivor iterative timing recovery outperforms the conventional receiver. Therefore, per-survivor iterative timing recovery is more robust against TA than the conventional receiver.

7. REFERENCES

[1] R. D. Hempstead, "Thermally induced pulses in magnetoresistive heads," *IBM J. Res. Develop.*, vol. 18, pp. 547–550, Nov 1974

[2] J. W. M. Bergmans, *Digital baseband transmission and recording*. Boston, Massachusetts: Kluwer Academic Publishers, 1996.

[3] P. Kovintavewat, M. F. Erden, E. M. Kurtas, and J. R. Barry, "Robustness of Per-Survivor Iterative Timing Recovery in Perpendicular Recording Channels," *IEEE International Conference on Magnetics* (INTERMAG 2005), Nagoya, Japan, pp. 1613 - 1614, April 4 - 8, 2005.

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

[5] P. Kovintavewat, J. R. Barry, M. F. Erden, and E. M. Kurtas, "Per-survivor iterative timing recovery for coded partial response channels," in *Proc. of Globecom 2004*, vol. 4, pp. 2604-2608, Nov 2004.

[6] Jaekyun Moon and Weining Zeng, "Equalization for maximum likelihood detector," *IEEE Trans. on Magnetics*, vol. 31, no. 2, pp. 1083-1088, Mar 1995.

[7] K. Mueller and M. Müller,"Timing recovery in digital synchronous data receivers," *IEEE Trans. on Commun.*, 24:516-531, May 1976.

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

[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] P. Kovintavewat, J. R. Barry, M. F. Erden, and E. M. Kurtas, "Reduced-complexity per-survivor iterative timing recovery for coded partial response channels," in *Proc. of ICASSP'05*, vol. 3, pp. iii/841 - iii/844, 2005.

[11] R. Raheli, A. Polydoros, and C. K. Tzou, "Per-survivor processing: A general approach to MLSE in uncertain environments," *IEEE Trans. on Commun.*, vol. 43, no. 2, pp. 354-364, Feb./Mar./Apr. 1995.

[12] J. Hagenauer and P. Hoeher, "A Viterbi algorithms with soft-decision outputs and its applications," in *Proc. of Globecom 1989*, pp. 1680–1686, Nov 1989.

[13] S. E. Stupp, M. A. Baldwinson, and P. McEwen, "Thermal asperity trends," *IEEE Trans. on Magnetics*, vol. 35, pp. 752–757, Mar 1999.

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