SIGNAL PRECOMPENSATION FOR MULTIPLICATIVE NOISE IN MAGNETIC RECORDING

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Abstract

Magnetic recording system design based on optimizing the write signal to account for multiplicative medium noise is described. The design involves placing three heads along the recorded track and is dubbed a write-read-write scheme. Medium noise has a repeatable spatial dependence, allowing compensation for local effects in addition to global average effects. A block diagram level system design is given that is capable of real-time implementation.

1 Introduction

Magnetic media may be viewed as signal processing systems in the sense that the magnetic field applied to the medium is transformed into a magnetic pattern on the surface of the medium. At a macroscopic level, for physically large distances between magnetic transitions (which correspond to recorded bits), the medium processing may be modeled as recording the applied magnetic field directly (there are other assumptions that enter into this having to do with the saturation of the medium and the use of applied magnetic fields with amplitudes in a prescribed range). However, if the physical distances between written transitions decrease enough, the magnetic microstructure of the medium itself becomes significant and the approximation described above is no longer valid. In the limit, prediction of the resulting magnetization must be based on micromagnetic medium models [6, 10]. There is a middle ground as well, where the medium is not modeled as being ideal, but the detailed micromagnetic computations are not required.

A model for operating in this middle ground is described here. In addition, the design of a novel signal precompensation scheme is described. This model includes multiplicative noise; an algorithm based on additive noise models was given in [5].

Rather than modeling the medium directly, the effects of the medium and the write and read heads on a signal sent through the channel is modeled. The channel is modeled as introducing signal-dependent noise that equals random variables times known transfer functions convolved with the signal:

$$y(t) = (b*s)(t) + \sum_{i=1}^{N} \theta_i \int h_i(t-\tau)s(\tau)d\tau + w(t), \quad (1)$$

where $s(t)$ is the data carrying signal, $b(t)$ is the ideal channel response, $*$ denotes convolution, θ_i are random variables, $h_i(t)$ are known functions, and $w(t)$ is additive white Gaussian noise.

Models of the form of (1) have been introduced in the literature by other authors [2, 7]. One common particular model includes the effects of peak-shift and amplitude-shift. If the desired signal is

$$h(t) = (b*s)(t), \quad (2)$$

then an amplitude-shifted, peak-shifted signal is given by

$$y(t) = ah(t-t_1) + w(t). \quad (3)$$

Using a first-order Taylor series approximation,

$$y(t) = h(t) + \theta_1 h(t) + \theta_2 \frac{dh}{dt}(t) + w(t), \quad (4)$$

where $\theta_1 = a - 1$ is the amplitude shift and $\theta_2 = -t_1$ is the peak shift.

In (1) and (4) the random variables θ_i are modeled as being dependent on the spatial location of the recording. That is, they do not depend on time, but the writing of a similar waveform at two time instants, at the same physical location on the medium, yields the same realization of the random variables θ_i. This model is consistent with experimental results demonstrating the repeatability of medium noise. These results have yielded a novel method for identification of media based on what is called a 'magnetic fingerprint' [4].

The proposed signal precompensation scheme involves a novel design of the recording protocol, called write-read-write recording which is shown in figure 1. This scheme was proposed for additive noise models in [5]. The concept is to have three heads along the track. The first head writes a signal at a given location on the medium, the second head reads the written signal. Then parameters in the model are estimated and used to modify the data signal; this modified data signal is then written by the second write head (the third head) on the medium.

The following section describes medium noise models in more detail. The design of the system using the multiplicative noise model (1) is described in Section 3.

This scheme may be modified for use in transmitter optimization in slowly fading channels. In that case, the design relies on feedback from the receiver to the transmitter. This design will be introduced in a future paper.

2 Medium-noise models

Magnetic recording channels have three main sources of noise: electronics noise, head noise, and medium noise. Development in the electronics of the magnetic recording channels have reduced electronic noise significantly. However as recording density increases, medium noise becomes more dominant [8].

Medium noise is a non-stationary random process, and it has been shown to have spatial and signal dependence [3, 11]. It is spatially dependent in the sense that medium noise at the same position of a DC erased disk (with an intervening DC erasure in the opposite direction) is highly correlated [3]. It is signal dependent in the sense that similar recording patterns at different locations on the disk yield similar medium noise [11].

Medium noise arises from random fluctuations in the medium magnetization or from any spatially random property of the medium which will give rise to noise in the final output [1]. In thin film media, amplitude modulation and particulate noise are virtually absent and the most important source of noise is transition noise which arises from the imperfect transitions written on the medium.

Several authors have described models for signal dependent transition noise [2, 11, 9]. These models have been computed using both approximate methods [2] and analytic methods based on Karhunen-Loeve expansions [11, 9]. Qualitatively, the principal functions in the Karhunen-Loeve expansion resemble the approximate expansion [9]. Here, either expansion method may be used, but the Karhunen-Loeve approach must be augmented to include the variation of the eigenfunctions with the written signal. In order to keep the presentation specific, we use the approximate expansion.

3 System Design

In this section we model medium-noise as a linear combination of the outputs of N linear time-invariant systems driven by the input to a magnetic recording channel. Weights of this linear combination are modeled to be random variables with their statistics depending on the particular place on the disk where the input signal is being written. Including additive white Gaussian noise, the overall noise in the output for the input signal $s(t)$ is given by

$$n(t) = \left[\sum_{i=1}^{N} \theta_i h_i(t)\right] * s(t) + w(t)$$

where the first term denotes medium noise and the second term denotes Gaussian noise in the output. We define $\theta = [\theta_1, \theta_2 \ldots \theta_N]^T$ and $L = [h_1(t), h_2(t) \ldots h_N(t)]^T$. With these definitions we can write $n(t) = [\theta^T L] * s(t) + w(t)$. Our objective is to minimize the output noise in the second read-back signal of the write-read-write scheme.

The output of a second read after the second write is modeled as

$$y_2(t) = (b * s_2)(t) + \left[\sum_{i=1}^{N} \theta_i h_i(t)\right] * s_2(t) + w_2(t),$$

where $s_2(t)$ is the second write signal and $w_2(t)$ is the additive noise in the second read. Without loss of generality, expand the second write signal as $s_2(t) = s_1(t) + \sigma(t)$. The ideal output signal is $(b * s_1)(t)$. The design goal is to minimize the expected distortion between the actual signal part of the output and the ideal output.

Design Problem Statement: Given the first read signal $y_1(t)$, select $\sigma(t)$ to minimize the expected value of

$$\left[\left\langle \theta^T L(\sigma + s_1) + b * \sigma, \theta^T L(\sigma + s_1) + b * \sigma \right\rangle\right]. \quad (5)$$

Gaussian Assumption: Assume that the random vector θ is Gaussian distributed with zero mean and covariance matrix R_θ. Assume that θ is independent of $w_2(t)$.

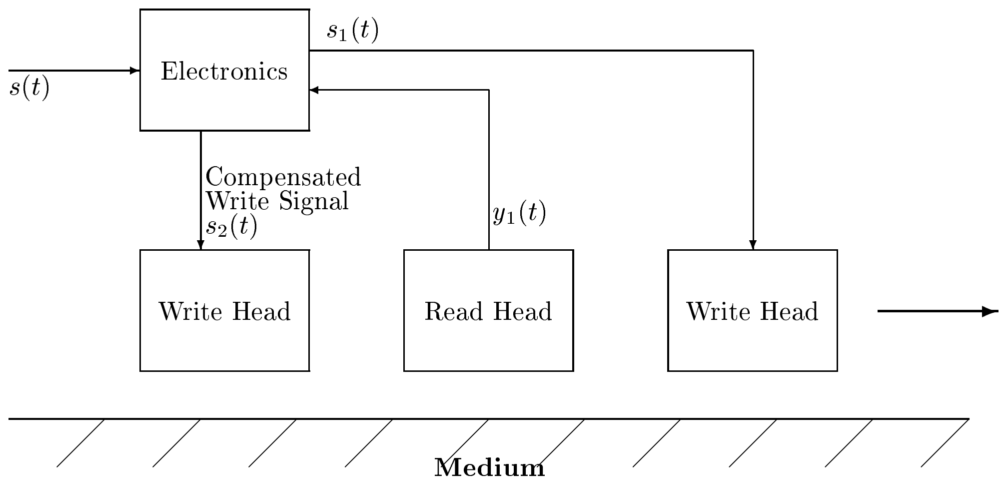

Figure 1: Block diagram of write-read-write scheme where the heads move to the right.

Note that under the Gaussian assumption, the conditional expected value of θ given $y_1(t)$ is also a Gaussian random vector. Denote its mean by $\hat{\theta}$ and its correlation matrix by $\hat{K_\theta}$. The matrix $\hat{K_\theta}$ does not depend on the measurement $y_1(t)$.

Lemma 1 *Under the Gaussian assumption, the* $\sigma(t)$ *that solves the design problem satisfies*

$$\begin{aligned} &- b(-t) * \left[\hat{\theta}^T L\right] * s_1(t) = \\ &\quad \mathtt{Tr}\left[\hat{K_\theta} L^* L^T\right] * (\sigma(t) + s_1(t)) \\ &\quad + b(-t) * b(t) * \sigma(t) + b(-t) * \left[\hat{\theta}^T L\right] * \sigma(t) \\ &\quad + [\hat{\theta}^T L^*] * b(t) * \sigma(t) \end{aligned}$$

The equation in the lemma may be solved using Fourier transform techniques to give

$$\Sigma(\omega) = \\ -S_1(\omega) \frac{\hat{\theta}^T C + \mathtt{Tr}\left[\hat{K_\theta} C^* C^T\right]}{1 + \mathtt{Tr}\left[\hat{K_\theta} C^* C^T\right] + \hat{\theta}^T C + \hat{\theta}^T C^*}, \quad (6)$$

where $\Sigma(\omega)$ is the Fourier transform of $\sigma(t)$, $C(\omega) = L(\omega)/B(\omega)$, $L(\omega)$ is the Fourier transform of the vector $L(t)$, and $B(\omega)$ is the transform of $b(t)$. Expanding $\hat{K_\theta} = \hat{R_\theta} + \hat{\theta}\hat{\theta}^T$ and using the identity $\mathtt{Tr}\left[\hat{\theta}\hat{\theta}^T C^* C^T\right] = \left|\hat{\theta}^T C\right|^2$,

$$\begin{aligned} \Sigma(\omega) &= \\ &-S_1(\omega) \frac{\hat{\theta}^T C \left[1 + \hat{\theta}^T C^*\right] + \mathtt{Tr}\left[\hat{R_\theta} C^* C^T\right]}{\left|1 + \hat{\theta}^T C\right|^2 + \mathtt{Tr}\left[\hat{R_\theta} C^* C^T\right]} \\ &= -S_1(\omega) \frac{\hat{\theta}^T C + \frac{\mathtt{Tr}\left[\hat{R_\theta} C^* C^T\right]}{1 + \hat{\theta}^T C^*}}{1 + \hat{\theta}^T C + \frac{\mathtt{Tr}\left[\hat{R_\theta} C^* C^T\right]}{1 + \hat{\theta}^T C^*}} \end{aligned} \quad (7)$$

Thus the second write signal $s_2(t) = s_1(t) + \sigma(t)$ can be generated as

$$\begin{aligned} S_2(\omega) &= S_1(\omega) + \Sigma(\omega) \\ &= S_1(\omega) \frac{1}{1 + \hat{\theta}^T C + \frac{\mathtt{Tr}\left[\hat{R_\theta} C^* C^T\right]}{1 + \hat{\theta}^T C^*}} \end{aligned} \quad (8)$$

A block diagram that implements (8) is shown in figure 2. The simple structure of this block diagram implies that real-time implementation may be possible.

4 Conclusions

In this paper, a method for designing a write-read-write recording scheme to account for multiplicative noise is described. Furthermore, a block-diagram level implementation of this scheme is described that is amenable to realization in actual systems. Future work includes extending the ideas used here to transmitter design for slowly fading communication channels.

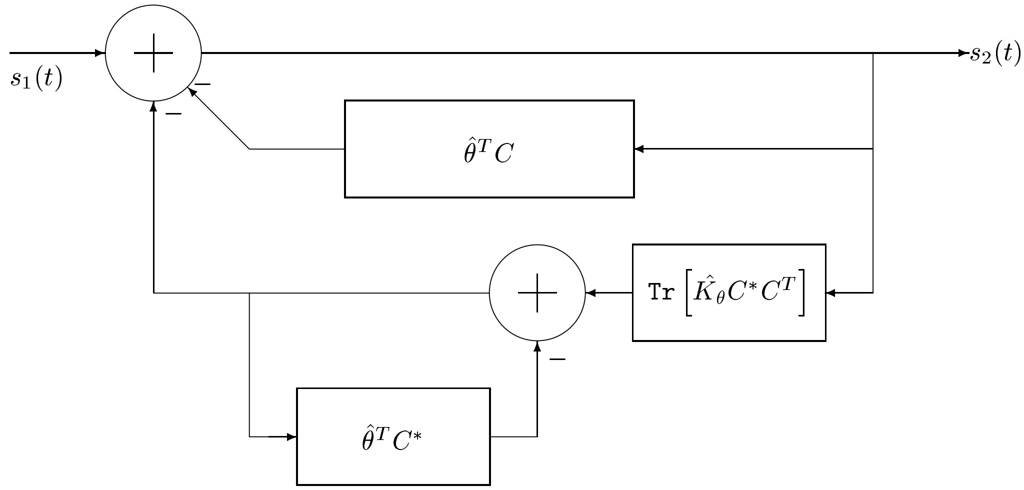

Figure 2: Block diagram of electronics for the second write. Result of first read enters through the estimate $\hat{\theta}$.

5 Acknowledgment

This work was supported in part by NSF grant NCR-9406197.

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