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Design of Noise Predictive Maximum Likelihood (NPML) Detector with Jitter Noise in Perpendicular Recording Channels

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Abstract— **Partial-response maximum-likelihood (PRML) is a technique that uses a PR equalizer in conjunction with the Viterbi detector (VD) to detect the readback signal in magnetic recording systems. In practice, PRML performs best if the noise component seen at the input of the VD is white noise. However, at ultra high storage capacities, noise-predictive maximum-likelihood (NPML) is used instead of PRML because the noise seen at the input of the VD appears to be colored noise. This NPML embeds the noise predictor in the VD so as to whiten only the colored noise. Nonetheless, it is well-known that media jitter noise is a dominant noise source in perpendicular recording channels. It is clear that this media jitter noise will degrade the performance of the NPML detector. This paper proposes a method to design the NPML detector in the presence of media jitter noise. Numerical results show that the proposed NPML detector performs better than the conventional NPML detector when media jitter noise is high, especially at high signal-to-noise ratio.**

Index Terms—**Equalizer and target design, Media jitter noise, Noise-predictive maximum-likelihood (NPML), Partial-response maximum-likelihood (PRML), Perpendicular recording**

I. Introduction

Magnetic recording systems practically employ a partial-response maximum-likelihood (PRML) technique [1], a technique of using the equalizer in conjunction with the Viterbi detector (VD) [2] for data detection process. PRML is done in two steps. First, the received signal is equalized to a PR target [3] whose response is as close to a channel response as possible. Then, the VD performs ML equalization on the resulting PR trellis [2]. It is well-known that the VD is an *optimal* detector if the noise component seen at the input of the VD is white noise. Nevertheless, at ultra high recording densities, the noise component seen at the VD input appears to be colored noise. In this case, the VD used in PRML reduces to a *sub-optimal* detector.

To improve the performance of PRML, a noise-predictive maximum-likelihood (NPML) technique [4] has been proposed to combat the colored noise. The NPML technique performs similar to the PRML technique, except that the noise prediction filter is utilized to whiten the colored noise before performing ML equalization by the VD. Although NPML performs better than PRML, especially at high recording densities, it has much higher complexity than PRML [4]. Clearly, there is a trade-off between the performance gain and the increased complexity. Thus, all advantages gained by NPML need to be balanced against the increased implementation cost.

It is known that media jitter noise [5] is a dominant noise source in perpendicular recording channels. This media jitter noise arises from deviation in the position of the transition pulse, which is non-stationary, correlated, and pattern dependent [5]. Apparently, the media jitter noise will definitely degrade the performance of the NPML detector.

Several methods have been proposed in the literature [6, 7, 8] to deal with media jitter noise. For example, Moon and Zeng [6] proposed a design of the target and its corresponding equalizer in the presence of media jitter noise based on a minimum mean-squared error (MMSE) approach. However, this method ignored the presence of the colored noise, thus performing bad at ultra high recording densities. On the other hand, Yang and Mathew [7] proposed a joint design of optimum PR target and its corresponding equalizer in the presence of media jitter noise. Again, this method is not suitable for operating at high storage capacities because of the colored noise. Then, Cai *et al*. [8] proposed a detector to combat media noise for optical recording systems. Nonetheless, this paper proposes a method to design the NPML detector in the presence of media jitter noise. This proposed NPML detector employs a *modified* noise predictor designed for a given amount of media jitter noise. It will be shown that the proposed NPML detector performs better than the conventional NPML detector when media jitter noise is high, especially at high signal-to-noise ratio (SNR).

This paper organizes as follows. After describing a system model in Section II, the design of the proposed NPML detector is explained Section III. Section IV briefly describes how the proposed NPML detector works. Simulation results are given in Section V. Finally, Section VI concludes this paper.

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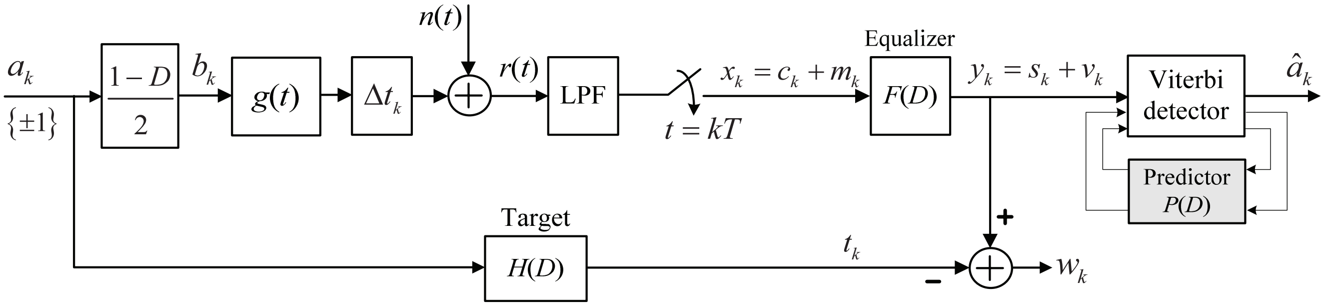

Fig. 1. System model with the design of the proposed NPML detector.

II. System Model

Consider a perpendicular recording system shown in Fig. 1. A binary input sequence $a_k \in \{\pm 1\}$ with bit period T is filtered by an ideal differentiator $(1 - D)/2$, where D is a unit delay operator, to obtain a transition sequence $b_k \in \{\pm 1, 0\}$, where $b_k = \pm 1$ 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 the magnetic recording channel represented by $g(t)$. The transition response $g(t)$ for perpendicular recording is given by [9] $g(t) = \mathrm{erf}(2t\sqrt{\ln 2} / \mathrm{PW}_{50})$, where erf(.) is an error function, ln(.) is a natural logarithm, 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 ND = PW_{50}/T, which determines how many data bits can be packed within PW_{50}.

The readback signal, $r(t)$, can then be expressed as

$$r(t) = \sum_k b_k g(t - kT - \Delta t_k) + n(t) \quad (1)$$

where $n(t)$ is an additive white Gaussian noise (AWGN) 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 Gaussian probability distribution function with zero mean and variance $|b_k|\sigma_j^2$ truncated to $T/2$ [10], where $|c|$ takes the absolute value of c.

At the receiver, the signal $p(t)$ is filtered by a seventh-order Butterworth low-pass filter (LPF), whose cutoff frequency is at $1/(2T)$, and is sampled at time $t = kT$ assuming perfect synchronization. The sampler output x_k is equalized by an equalizer $F(D)$ such that an equalizer output y_k closely resembles a desired sample t_k. Note that the design of a target $H(D)$ and its corresponding equalizer can be found in [6]. Then, the sequence y_k is fed to the VD to determine the most likely input sequence, $\hat{a}_k$.

III. A Modified Noise Predictor

To simplify the design of a modified noise predictor in the presence of media jitter noise, we first decompose the readback signal in (1) into two terms using the 1st-order approximation of the Taylor series [8], i.e,

$$r(t) \approx \sum_k b_k g(t - kT) + \sum_k b_k \Delta t_k g'(t - kT) + n(t), \quad (2)$$

where $g'(t)$ the derivative of $g(t)$. Thus, the sampler output can be expressed as

$$x_k = c_k + m_k, \quad (3)$$

where c_k is the wanted data corrupted by AWGN, and m_k is the unwanted data caused by media jitter noise (i.e., the contribution from the second term on the right-handed side in (2)).

Denote $F(D) = \sum_{k=-K}^{K} f_k D^k$ and $H(D) = \sum_{k=0}^{L-1} h_k D^k$ as the $(2K + 1)$-tap equalizer and the L-tap target, where K is an integer, L is the number of taps of the target, and f_k and h_k are the k-th coefficient of $F(D)$ and $H(D)$, respectively. Next, the sequence x_k is fed to the equalizer $F(D)$ to obtain a sequence $y_k = s_k + v_k$, where $s_k = c_k * f_k$ and $v_k = m_k * f_k$, where $*$ is a convolution operator. In general, the difference between the equalizer output y_k and the target output t_k is an error sequence w_k, which can also be considered as colored noise.

Practically, the power of colored noise can be reduced via noise whitening process as shown in Fig. 2, where $P(D) = \sum_{i=1}^{N} p_k D^k$ is a noise predictor filter, p_k is the k-th coefficient of $P(D)$ and N is the number of predictor taps. Then, the prediction error, e_k, can be written as

$$\begin{aligned} e_k &= w_k - \hat{w}_k = w_k - \sum_{i=1}^{N} p_i w_{k-i} \\ &= s_k + v_k - t_k - \sum_{i=1}^{N} p_i (s_{k-i} + v_{k-i} - t_{k-i}), \end{aligned} \quad (4)$$

because $w_k = y_k - t_k = s_k + v_k - t_k$ (see Fig. 1).

The predictor error filter is designed such that $E[e_k^2]$ is minimized in the minimum mean-squared sense using (5)

$$E\left[e_k^2\right] = E\left[\left(s_k + v_k - t_k - \sum_{i=1}^{N} p_i (s_{k-i} + v_{k-i} - t_{k-i})\right)^2\right] \quad (5)$$

where $E[.]$ is the expectation operator. To solve for the coefficients p_i's, we can minimize (5) with respect to p_i and set the result to zero. On the other hand, we can also apply the orthogonality principle [4] to (5) to obtain

$$E\left[\left(s_k + v_k - t_k - \sum_{i=1}^{N} p_i (s_{k-i} + v_{k-i} - t_{k-i})\right)(s_m + v_m - t_m)\right] = 0$$

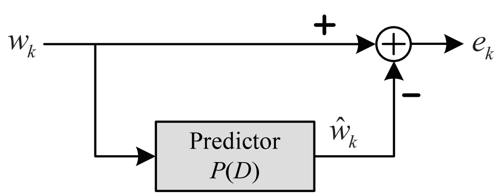

Fig. 2. Noise whitening process.

for $m = 1, 2, \ldots, N$. By solving the above equation, we obtain

$$R_{ss}(j)+R_{sv}(j)-R_{st}(j)+R_{vs}(j)+R_{vv}(j)-R_{vt}(j)$$
$$-R_{ts}(j)-R_{tv}(j)+R_{tt}(j) = \sum_{i=1}^{N} p_i \{R_{ss}(j-i)+$$
$$R_{sv}(j-i)-R_{st}(j-i)\ R_{vs}(j-i)+R_{vv}(j-i)$$
$$-R_{vt}(j-i)-R_{ts}(j-i)-R_{tv}(j-i)+R_{tt}(j-i)\}, \quad (6)$$

for $j = 1, 2, \ldots, N$, where R_{ss}, R_{sv}, R_{st}, R_{vs}, R_{vv}, R_{vt}, R_{ts}, R_{tv}, and R_{tt} are correlation functions. Equation (6) can also be rewritten in a matrix form as

$$\underbrace{\mathbf{r}_1+\mathbf{r}_2-\mathbf{r}_3+\mathbf{r}_4+\mathbf{r}_5-\mathbf{r}_6-\mathbf{r}_7-\mathbf{r}_8+\mathbf{r}_9}_{\mathbf{r}}$$
$$=\underbrace{(\mathbf{R}_1+\mathbf{R}_2-\mathbf{R}_3+\mathbf{R}_4+\mathbf{R}_5-\mathbf{R}_6-\mathbf{R}_7-\mathbf{R}_8+\mathbf{R}_9)}_{\mathbf{R}}\mathbf{p} \quad (7)$$

where $\mathbf{r}_1$, $\mathbf{r}_5$, and $\mathbf{r}_9$ are N-by-1 autocorrelation matrices of s_k, v_k, and t_k, respectively; $\mathbf{r}_2$ and $\mathbf{r}_4$ are N-by-1 cross-correlation matrices between s_k and v_k, where $R_{sv}(j) = R_{vs}(-j)$; $\mathbf{r}_3$ and $\mathbf{r}_7$ are N-by-1 cross-correlation matrices between s_k and t_k, where $R_{st}(j) = R_{ts}(-j)$; $\mathbf{r}_6$ and $\mathbf{r}_8$ are N-by-1 cross-correlation matrices between v_k and t_k, where $R_{vt}(j) = R_{tv}(-j)$. In addition, $\mathbf{R}_1$, $\mathbf{R}_5$, and $\mathbf{R}_9$ are N-by-N autocorrelation matrices of s_k, v_k, and t_k, respectively; $\mathbf{R}_2$ and $\mathbf{R}_4$ are N-by-N cross-correlation matrices between s_k and v_k; $\mathbf{R}_3$ and $\mathbf{R}_7$ are N-by-N cross-correlation matrices between s_k and t_k; $\mathbf{R}_6$ and $\mathbf{R}_8$ are N-by-N cross-correlation matrices between v_k and t_k; and $\mathbf{p} = [p_1, p_2, \ldots, p_N]^T$ is an N-element column vector.

Because (7) reduces to a linear equation problem $\mathbf{r} = \mathbf{R}\mathbf{p}$ and $\mathbf{R}$ is a square matrix, the coefficients of the noise predictor, $\mathbf{p}$, can then be easily obtained by

$$\mathbf{p} = \mathbf{R}^{-1}\mathbf{r} \quad (8)$$

Note that the noise predictor $\mathbf{p}$ in (8) is designed in the presence of media jitter noise. Thus, the proposed PRML detector that employs this noise predictor should perform better than the conventional NPML detector that uses the noise predictor designed in the absence of media jitter noise.

IV. Proposed NPML Detector

To simplify the implementation of the proposed NPML detector as studied in [4], we focus on the proposed NPML detector in

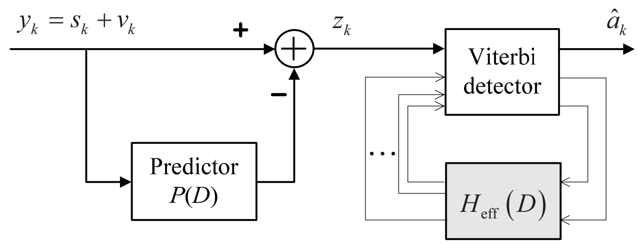

Fig. 3. How the NPML detector performs.

Fig. 3. Specifically, the equalizer output y_k is first filtered by the predictor error filter $(1 - P(D))$ to obtain a sequence z_k, i.e.,

$$z_k = y_k - \sum_{i=1}^{N} p_i y_{k-i} . \quad (9)$$

Then, the sequence z_k is fed to the Viterbi detector that uses the *effective* target [4] to implement the trellis diagram for ML equalization. This effective target, $H_{\text{eff}}(D)$, is given by

$$H_{\text{eff}}(D) = H(D)[1 - P(D)], \quad (10)$$

where H(D) is the target designed to match the equalizer $F(D)$ based on the MMSE approach [3]. Thus, the VD used in the NPML system will have the number of trellis states equal to $2^{\mu+N}$ states, where $\mu = L - 1$ is the target memory, whereas the VD employed in the PRML system will have the number of trellis states equal to 2^{μ} states. Evidently, the NPML system has more complexity than the PRML system.

V. Simulation Result

We consider the perpendicular recording channel at ND = 3. The SNR is defined as SNR = $10\log_{10}(E_i/N_0)$ in decibel (dB), where E_i is the energy of the channel impulse response (i.e., the derivative of the transition response scaled by 2). The PR target and its corresponding 11-tap equalizer was designed at the SNR required to achieve BER = 10^{-5} in the absence of media jitter noise. The 2-tap noise predictor filter is utilized in NPML. Each BER point is computed using as many 4096-bit data sectors as needed to collect at least 1000 error bits.

In simulation, we compare the performance of the proposed NPML with the conventional NPML and the PRML, where the PR2 target (i.e., $H(D) = 1 + 2D + D^2$) is used in both NPML systems and the EEPR2 target (i.e., $H(D) = 1 + 4D + 6D^2 + 4D^3 + D^4$) used in the PRML system.

Fig. 4 compares the performance of different schemes at 6% media jitter noise. Apparently, the proposed NPML performs better than the conventional NPML scheme and the PRML only when SNR is high. This is because colored noise is dominated at low SNR, whereas media jitter noise will be dominated at high SNR. Therefore, at high SNR, using the proposed NPML detector designed in the presence of media jitter noise will yield good performance if compared to the conventional NPML and the PRML designed in the absence of media jitter noise. Moreover, the reason the PRML performs better than the conventional NPML might be because

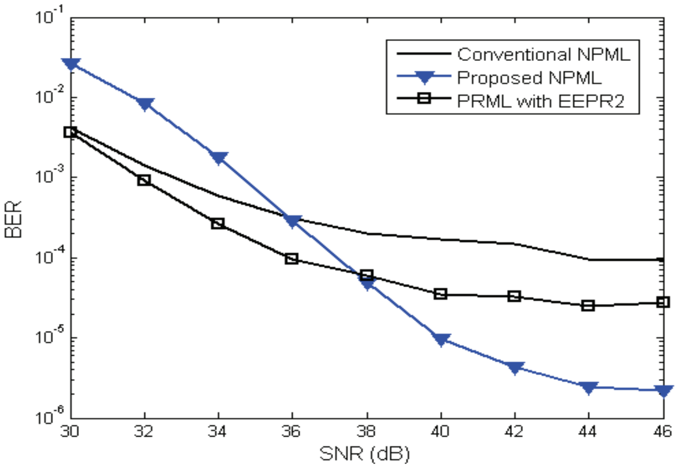

Fig. 5. BER performance of different schemes with 6% media jitter noise.

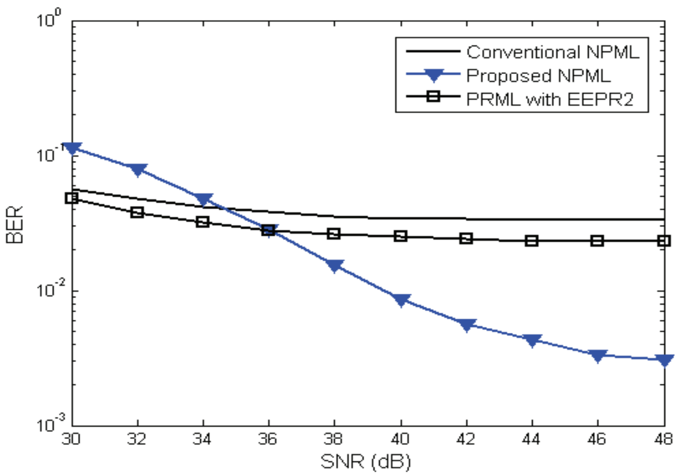

Fig. 6. BER performance of different schemes with 12% media jitter noise.

the target used in the PRML has a better match to the channel at ND = 3 than the conventional NPML.

We also compare the performance of different schemes at 12% media jitter noise in Fig. 6. In this case, we see that the proposed NPML performs even better than the conventional NPML and the PRML at high SNR. Again, this is because media jitter noise is dominated at high SNR. This can be verified by looking at the correlation of w_k because it will be used to design the noise predictor. Practically, the higher the correlation of w_k, the better the performance of the noise predictor. Fig. 7 plots the mean-squared correlation (MSC) of w_k of two NPML systems at 12% media jitter noise, where the MSC is defined as MSC = $\frac{1}{M}\sum_{i=0}^{M} R_{ww}(i)$ where $R_{ww}(k)$ is a autocorrelation function of w_k, and M = 10 is used for simplicity (because the first few $R_{ww}(k)$'s will have large value). Clearly, at SNR > 36 dB, the proposed NPML has larger MSC and lower BER than the conventional NPML as expected.

VI. Conclusion

At high storage capacities, the PRML has been replaced by the NPML to combat the colored noise. However, it is known

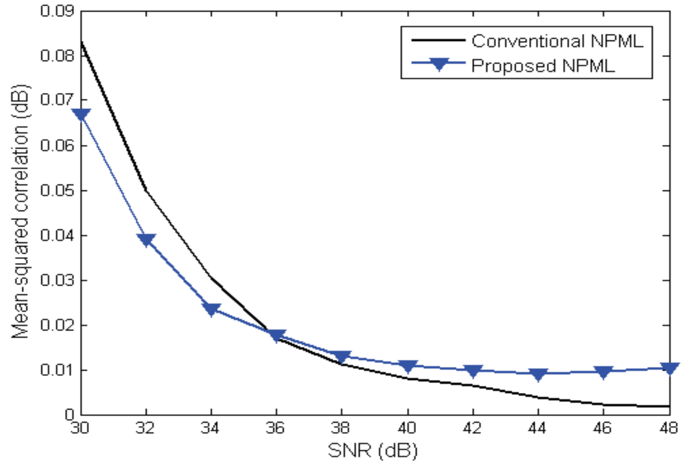

Fig. 7. MSC of an error sequence w_k at 12% media jitter noise.

that media jitter noise is a dominant noise source in perpendicular recording channels. This paper proposes the design of the NPML detector in presence of media jitter noise, which has been shown to perform better than the conventional NPML detector that is designed in the absence of media jitter noise, especially at high SNR.

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