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Target and Equalizer Design for Perpendicular Magnetic Recording at 1 Tb/in^2

Sukarasut Meksiri, Skawrat Wangtaphan, and Kasin Vichienchom
Department of Electronics, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520 Thailand
Email: kvkasin@ kmitl.ac.th

***Abstract*—This paper described the design of generalized partial-response (GPR) target and its corresponding equalizer for perpendicular magnetic recording (PMR) read channel with jitter noise. In this design the readback signal model uses transition response that its parameter is calculated based on media properties and reader head geometry specifically designed for 1 Tb/in^2 areal density. The GPR targets with various lengths are designed using minimum mean-squared error (MMSE) approach. The simulation results show that the BER performance of the system degrades as the ratio of jitter noise power to total noise power increases. According to these results GPR2 with 7-tap equalizer offers the optimal tradeoff between system performance and circuit implementation.**

***Index Terms*—Perpendicular magnetic recording, partial response target deign, jitter noise, equalizer.**

I. INTRODUCTION

THE demands of continually increasing storage capacity and data transfer rate have been a major driving force for the significant progress of the today hard disk drive technology. Newly developed composite media that greatly improve their writeability have been proposed [1]. The change of recording scheme from longitudinal magnetic recording (LMR) to perpendicular magnetic recording (PMR) enables high-density magnetic recording beyond the super-paramagnetic limit [2]. The indispensable advancements in signal processing and integrated circuit technology make a high speed and low-power read channel System-on-a-Chip (SoC) possible. Due to all of these, it is expected that with PMR a hard disk drive with the areal density of terabit per square inch and data transfer rate of gigabit per second will soon be available commercially.

Unlike LMR, PMR uses a thicker recoding layer with soft underlayer resulting in higher write fields and stronger playback signal. Compared to LMR, it alleviates the thermal stability problem yielding less transition jitter and higher SNR [3]. Furthermore from the signal processing point of view, the location in frequency of their main signal energy is different. While LMR readback signal is a dc-free signal, the PMR readback signal contains significant information at low frequency including dc. Therefore signal processing has been changed to make it more suitable for low frequency response of the signal.

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This includes applying a PRML target polynomial that contain dc response i.e. target of the form $(1+D)^n$ [2][4][5]. In addition it has been shown that the generalized partial response (GPR) target with arbitrary coefficients gives a superior performance to a dc-full response PR target with integer coefficients [2][6]. This because its non-integer coefficients enable a more accurate channel match with various readback signals, thus allow us to minimize equalization enhancement of white noise as well as provide better channel spectrum matching in high frequency region..

In this paper PRML target and its corresponding equalizer for PMR read channel at 1 Tb/in^2 areal density is designed and evaluated with several noise conditions. For optimal performance the GPR target and minimum mean-squared error (MMSE) equalization technique [7] are employed .To be more realistic we use a transition response that its pulsewidth T_{50} is calculated based on media properties and reader head geometry specifically designed for 1 Tb/in^2 [1][8]. The simulation results show that at such a high areal density, the normalized recording density (ND) is approximately one. As a result, the GPR target with order 2 is enough to provide an acceptable performance. Consequently the hardware implementation of its equalizer and Viterbi detector can be minimized.

This paper is organized as follows. The next section describes the channel model used in this paper. The design of GPR target is then explained in Section III. In Section IV, simulation results of the system with and without jitter noise are presented. Finally Section V concludes the paper.

II. MODEL OF PMR READ CHANNEL

A. Signal Model .

The readback signal used in our model is produced by a current perpendicular to plan (CCP) giant magnetoresistive (GMR) reader. The transition response is given by [8]

$$g(x) = V_{\max} erf\left(\frac{0.954x}{T_{50}}\right) \tag{1}$$

where $V_{\max}$ is the maximum value of signal read from the sensor and T_{50} is the distance between the positions of the sensor where the signal is 1/2 and -1/2 from its maximum value. According to [1] for the areal density of 1.01 Tb/in^2 and bit length B of 10.2 nm, the T_{50} is estimated to be 9.6 nm. Therefore the normalized recording density ND which is defined as ratio between T_{50} and B is equal to 0.94.

The dibit response is then given by

$$s(x) = (g(x) - g(x - B))/2 \tag{2}$$

To observe the difference between noiseless readback signal used in our model and the noiseless readback signal of the commonly used transition response

$$g_1(x) = V_{\max} erf\left(\frac{x\sqrt{\ln 16}}{PW50}\right) \tag{3}$$

their dibit responses, $s(x)$ and $s_1(x)$, at ND = 0.94 are plotted in Fig. 1. Shape of the dibit response indicates how strong inter-symbol interference (ISI) will be. The wider the pulsewidth the more severe ISI is. Clearly, at the same ND the readback signal of our model is worse than the commonly used one.

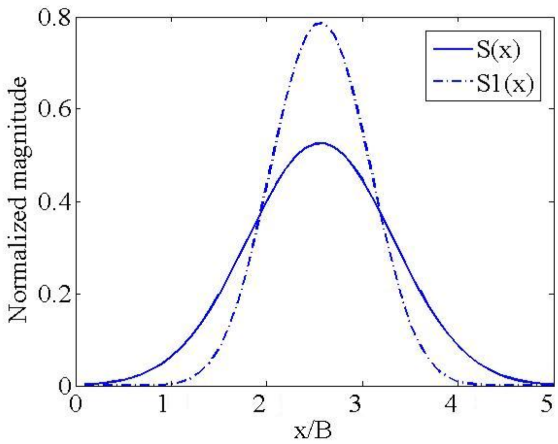

Fig. 1 Dibit responses of our model $s(x)$ and a commonly used model $s_1(x)$ at ND = 0.94

B. Noise Model

There are two major noises in PMR, electronic noise and media noise. The electronic noise represents noises from transducer and readback circuitry. It is modeled as a bandwidth-limited, additive white Gaussian noise (AWGN) with zero mean and variance σ_w^2 .The media noise or transition jitter noise (TJN) is the random shift of the transition position. It is data dependent and characterized through an independent Gaussian random variable α_k whose mean and variance are zero and σ_j^2 respectively.

C. Simplified Read Channel Model

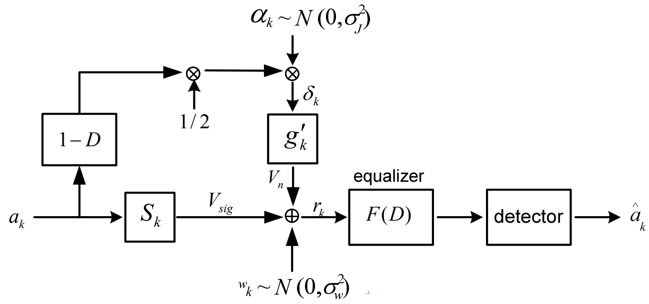

Fig. 2 Simplified read channel model

The channel model is shown in Fig. 2. Let $a_k \in \{-1,+1\}$ be the recorded data. The noiseless $V_{sig}(x)$ signal is given by a convolution a_k of and the dibit response, thus

$$V_{sig}(x) = \sum_k a_k s(x - kB). \tag{4}$$

The noise is composed of the AWGN given w_k by and the TJN given by

$$V_n(x) = \sum_k \alpha_k \left(\frac{a_k - a_{k-1}}{2}\right) g'(x - kB) \tag{5}$$

Therefore the received signal after low-pass filtering and sampling with sampling interval B can be expressed as

$$r_k = V_{sig}(kB) + V_n(kB) + w_k \tag{6}$$

The sampled signal is then equalized by a finite-impulse-response (FIR) filter calculated to minimize the mean-squared-error (MSE) of the equalizer output and the target response before passing through a Viterbi detector.

The channel signal-to-noise ratio (SNR) is defined as

$$SNR = 10\log_{10}\left(\frac{V_{\max}^2}{\sigma_w^2 + \sigma_j^2 \,\| g'(x) \|^2}\right) \tag{7}$$

Note that according to this definition when we evaluate the system performance at different level of jitter noise for example at jitter noise 10 percent, it means that jitter noise power is 10 percent of total noise power.

III. TARGET AND EQUALIZER DESIGN

In this paper, we design GPR target and equalizer based on the widely used minimum mean-squared error (MMSE) technique. Due to its tendency to whiten the noise sample at its output this approach by imposing a monic constraint on the target step response results in the performance nearly equal to that of the optimal system [7]. Fig. 3 shows the MMSE equalizer design.

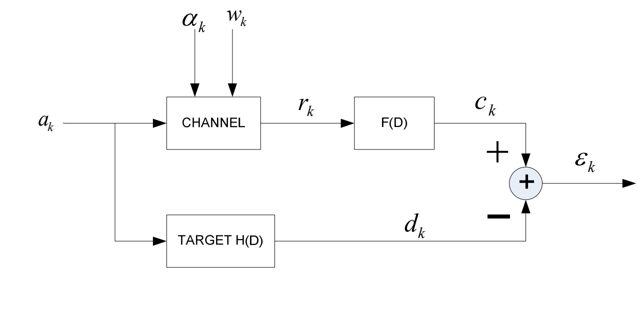

Fig. 3 MMSE Equalizer deign

From Fig. 3 H(D) is the GPR target with length L and its time domain coefficients are described by $\mathbf{H} = [h_0\ h_1\ h_2.\ .\ h_{L-1}]$. F(D) is the equalizer with length $N = 2K + 1$ and its time domain coefficients are described by $\mathbf{F} = [f_{-K}\ f_{-K+1} \ldots f_{K-1}\ f_K]^T$. $[\bullet]^T$ is the transpose operation. Let $\mathbf{R}$ be an N-by-N matrix with its (i,j) th element given by $R_{ij} = E\{r_{k-i}\, r_{k-j}\}$, where $-K \le i,j \le K$. Let $\mathbf{A}$ be an L-by-L matrix with $A_{ij} = E\{a_{k-i} a_{k-j}\}$, where $0 \le i,j \le L-1$ and $\mathbf{P}$ be an N-by-L matrix with $M_{ij} = E\{r_{k-i}\, a_{k-j}\}$, where $-K \le i \le K$ and $0 \le j \le L-1$. Let ε_k be the difference between the equalizer output c_k and the target output d_k . The mean squared error can be written as

$$E\{\varepsilon^2\} = \mathbf{F}^T\mathbf{RF} + \mathbf{H}^T\mathbf{AH} - 2\mathbf{F}^T\mathbf{PH} \qquad (8)$$

To minimize the mean squared error in (7) and avoid reaching the trivial solution of $\mathbf{H} = \mathbf{F} = \mathbf{0}$ we use the monic constraint i.e. $h_0 = 1$. Consequently, we can obtain[7]

$$\lambda = \frac{1}{\mathbf{I}^T(\mathbf{A} - \mathbf{P}^T\mathbf{R}^{-1}\mathbf{P})^{-1}\mathbf{I}}$$

$$\mathbf{H} = \lambda(\mathbf{A} - \mathbf{P}^T\mathbf{R}^{-1}\mathbf{P})^{-1}\mathbf{I}$$

$$\mathbf{F} = \mathbf{R}^{-1}\mathbf{PH}$$

where λ is the Langrange multiplication and $\mathbf{I} = [1\ 0\ 0\ \ldots 0]^T$ is vector of length L .

To realize the system it is important to select the proper number of L and K. There is a tradeoff between the system performance in term of BER and its hardware implementation. Typically increasing L and K improves detection performance at high recording density. Simultaneously, it also requires larger detector and equalizer circuit hence increasing chip area and power consumption. To assist the design we compare frequency response of dibit to target with various lengths. As shown in Fig. 4 the longer target length yields the better spectrum matching. However there is only small difference among responses of each target. Therefore to minimize hardware required we select GPR target with length $L = 3$ (GPR2). Based on the GPR2 target, FIR equalizers are designed using $K = 3$, 7 and 10 and center tap is at k = 0.

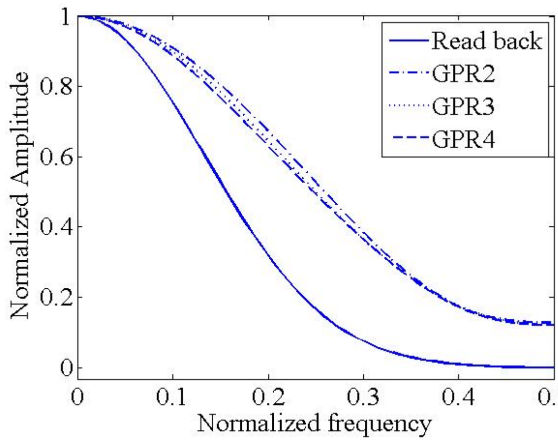

Fig.4 Frequency spectrum of readback signal compare to GPR target frequency response at ND = 0.94

IV. Performance Evaluation

Performance evaluations of the PMR read channel were done using computer simulation under the following conditions. Readback signal is of 1 Tb/in^2 areal density with ND = 0.94. GPR target length is 3. The numbers of equalizer tab are 7, 15 and 21. Noise is a mixture of AWGN from electronic circuitry and TJN from media. SNR is defined as in (7). The amount of TJN is specified as a percent of total noise power. In order to reduce amount of computation time, BER is computed using the *effective signal-to-noise ratio* (SNR_{eff}) [6][7]. The SNR_{eff} however can be used to estimate BER only in the case of low jitter noise [6]. Therefore we used this approach to calculate the BER performance versus SNR of the channel with three different amounts of jitter noise, 0%, 5% and 10%. The results are shown in Fig. 5 for each equalizer.

As illustrated in Fig. 5, all thee designs result in an acceptable BER (< 10^{-5}) for SNR is greater than 19 dB. Note that at the same amount of total noise power the BER performance degrades as percent of TJN increases. This is due to the fact that the target contains dc response therefore it is susceptible to low frequency characteristic of TJN. This agrees with results in [2]. In addition for the equalizer design we observe that there is no significant SNR improvement by increasing number of equalizer tab. Thus 7-tap FIR equalizer will be our best choice since it requires the least hardware.

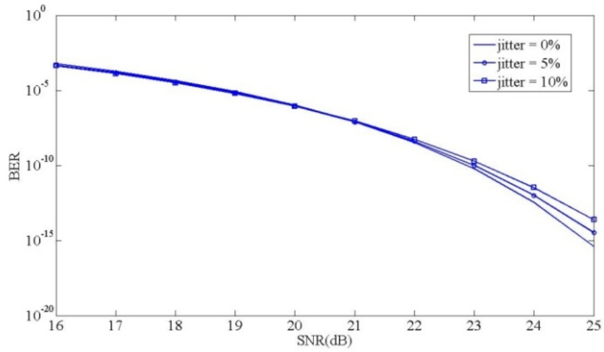

Fig. 5 (a) BER versus SNR (dB) with various amount of jitter of the channel using 21-tap equalizer

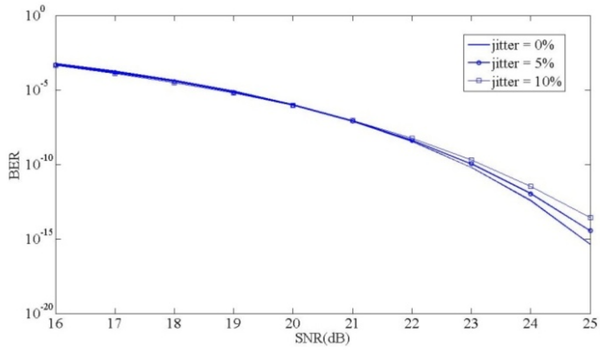

Fig. 5 (b) BER versus SNR (dB) with various amount of jitter of the channel using 15-tap equalizer

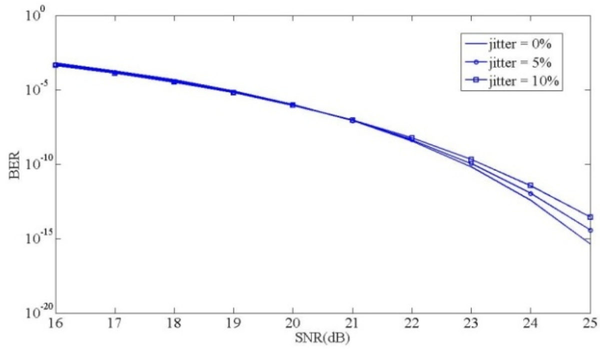

Fig. 5 (c) BER versus SNR (dB) with various amount of jitter of the channel using 7-tap equalizer

V. Conclusion

We have described the design and performance of a PRML read channel for PMR system. The signal model uses transition response that its pulsewidth T_{50} is calculated based on media properties and reader head geometry specifically designed for 1 Tb/in^2 areal density. For optimal performance the GPR target and minimum mean-squared error (MMSE) equalization technique are employed. The simulation results show that as the ratio of jitter noise power to total noise power increases the BER performance decreases. According to these results GPR2 with 7-tap equalizer offers the optimal tradeoff between system performance and circuit implementation.

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