A study on readback channel of Perpendicular Magnetic Recording system

Magnetic readback channel is a high-correlated ISI channel. By using modern digital signal processing techniques and channel coding schemes, the recording density of hard disk drive has been growing rapidly. In this report, we will summarize the readback channel model of Magnetic Recording systems, especially focus on the widely used perpendicular recording systems. The report will first give a full picture about the magnetic recording systems. Then, we will discuss the simplified readback channel model of perpendicular magnetic recording systems, including the electronic noise and media noise. At last, we will discuss the probable solutions in designing the error-correcting codes for 4k sector HDD in physical layer, and also the problems that may encounter.

1. Magnetic recording systems

Partial Response Maximum Likelihood (PRML) system is now a de facto standard in the HDD industry[1]. Fig. 1 is a generalized diagram for the magnetic recording system.

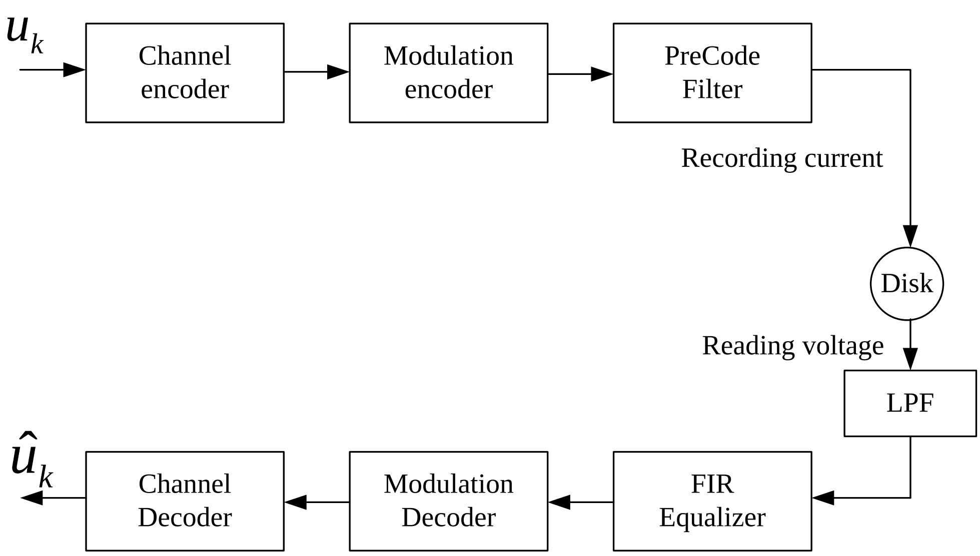

Fig. 1 A generalized diagram for magnetic recording system

In the magnetic recording system, the data bit stream u_k is first encoded by the channel encoder. After adding some parity bits, the coded bit stream passes the modulation encoder to add some constraint on the coded bit stream to facilitate the time recovery and bit detection. Then, the bit stream is filtered by a low-pass filter called precode filter to transform the transition status of the modulation encoder to the recording current (There is a postcode filter in the modulation decoder block functioning reversely). After the precoder, the data is recorded on the disk.

In the readback progress, the data stream first pass a low pass filter after it is read out from the disk. Then, the data stream enters the FIR equalizer. It detects the bit stream, including time recovery, signal detection. One of the most important parts, which is also the one we may be interested, is PRML detector. There are various kinds of PRML detectors, such as PRML, PR4ML, EPR4ML, and generalized PRML[2, 3]. The generalized polynomial form of PRML detector is $g(D) = (1 - D^2)(1 + c_1 D + c_2 D^2 + \cdots)$. The coefficients, called targets of PRML are determined by the system design, such as the recording density, readback head and so on. The main function of the PRML detector is following: shortening the length of response in order to reduce the ISI; performing the maximum-likelihood detection of the channel response. Noise Predictive Maximum Likelihood (NPML) detector[4] is state of art. The estimated data stream is then decoded sequentially by the modulation decoder and channel decoder. Finally, the data $\hat{u}_k$ is read out.

2. Readback channel model of perpendicular magnetic recording

The readback channel of magnetic recording systems is dependent on read head, magnetic materials, recording density, and inputting data and so on. In this section, we briefly introduce the major noises appear in the readback channel of perpendicular magnetic recording(PMR) system with high recording density, and then give a simplified channel model of the PMR based on the GMR head, thin-film materials.

There are mainly two kinds of noise existing in the magnetic recording channel: the one is electronic noise arises from the read head and pre-amplifier, which is usually modeled as AWGN; the other is media noise because of the granularity or particularity of the media, which is the dominant noise for high recording density[5]. The media noise also called transition noise because the noise is always induced during the signal transition progress. The media noise has high correlation with the media materials and the inputting data [6-8].

There are some researches on the study of media noise. One of the famous and physically based models is the micro-track model[9]. In the model, the media noise is composed of three noises: position jitter noise, pulse amplitude and width jitter noise, partial erasure noise. The model is complicated, and it is derived from actual observation. And it has several simplified version, such as Nair-Moon model[10, 11], Yamauchi-Lee-Cioffi model [12, 13]and so on. Later, we will show a simplified, easy to implement channel model of perpendicular magnetic recording system. This model is derived by making tradeoff between implementation complexity and actual observation. Before introducing the simplified model, we first give some basic definition of perpendicular recording channel.

$g(t)$: The single side response of one bit during transition[1];

$h(t)$: The dibit response of one bit during transition, so $h(t) = g(t) - g(t - T_s)$;

In the perpendicular magnetic recording systems,

$$g(t) = A \bullet \tanh\left(\frac{Log(3)t}{T_{50}}\right) \tag{1.1}$$

Where, A is the amplitude of the response, and T_{50} is the time duration when the response from $-\frac{A}{2}$ to $\frac{A}{2}$ (or from $\frac{A}{2}$ to $-\frac{A}{2}$). Usually, T_{50} is combined with the sampling period T_s of the magnetic recording system to describe the recording density, where there is another parameter $D_u = \frac{T_{50}}{T_s}$.

So, if there is no media noise, the channel response should be:

$$y(t) = \sum_{K=-\infty}^{K=\infty} u_k h(t - kT_s) + N(t) \tag{1.2}$$

In the simplified channel model of perpendicular magnetic recording system, the media noise is simplified to be a transition jitter noise. The transition jitter noise has a zero mean, and always modeled as Gaussian distributed, though it's actually not. So if we add this noise, the channel response should be:

$$y(t) = \sum_{K=-\infty}^{K=\infty} u_k h(t - kT_s + \Delta) + N(t) \tag{1.3}$$

Where Δ is the jitter noise, which has a distribution as $N(0, \delta_j^2)$. By further simplification, (1.3) could be reduced to (1.4) using Taylor expansion:

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[1] The response is a strictly physically based response, dependent on the read head, the media and so on.[14-16]

$$y(t) = \sum_{K=-\infty}^{K=\infty} u_k \left(h\left(t - kT_s\right) + \Delta g'\left(t - kT_s\right) \right) + N\left(t\right) \tag{1.4}$$

Where $g'\left(t\right) = \dfrac{dg(t)}{dt}$

So, the simplified channel model of perpendicular magnetic recording channel is as Fig. 2:

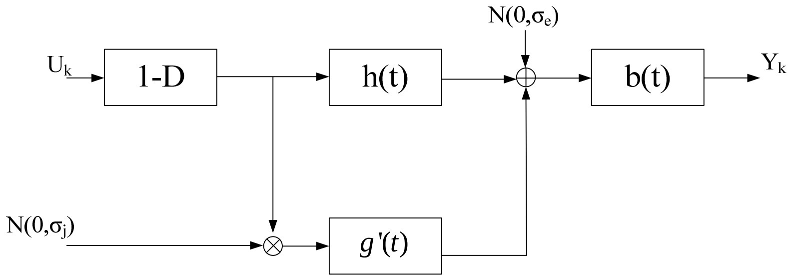

Fig. 2 Simplified readback channel model

In this model, there are two noises, which could both be implemented using Gaussian variables. The whole noise is composed of the two noise by fraction, which is variable according to different recording density. So the SNR of the model is:

$$SNR = 10\log_{10}\left(\frac{A^2}{\sigma_e^2 + \sigma_j^2 \left\| g'\left(t\right) \right\|^2} \right) = 10\log_{10}\left(\frac{A^2}{\sigma_e^2 + \dfrac{1-\beta}{\beta}\sigma_e^2 \left\| g'\left(t\right) \right\|^2} \right) \tag{1.5}$$

Where $\beta = \dfrac{\sigma_e^2}{\sigma_e^2 + \sigma_j^2}$.

3. Solutions and problems

As a new sector standard in HDD world, 4k sector standard provides more space for promoting the error correcting capability of HDD in physical layer. As a dominant noise in the modern magnetic recording density, jitter-like media noise could be described as a position shift in the time domain, which has high correlations with the input signal and magnetic recording media. Meanwhile, the signal processing mechanism of handling the transition response signal is another key issue when the recording density becomes more and more high. But in this report, we just consider the improvement in codes designing, and leave the signal synchronization and equalization problem to the de facto standard NPML. On the designing target of achieving one error per 10^16 bits [17], we have some ideas:

a. Designing new modulation codes. Since the jitter noise of the magnetic recording channel is highly correlated to the inputting signal, some constraints are needed on the recording signals before they are transformed into writing current. Recently, some new constraints codes such as MTR codes[18] and modulation schemes (Reverse concatenation)[19-21] are proposed. Maybe we could design some codes under the same constraint but have better performance in controlling the error propagation.

b. Study the error patterns of the NPML systems. NPML systems are widely used in the HDD industry. We could try to find out whether there are any correlations between the error patterns of such systems and jitter-like media noises, so as to facilitate the designing of error correcting codes.

c. Designing the AG-based codes. In order to achieve the comparably low decoding error floor, we think the graph codes with clear structure, such as QC-LDPC codes base on finite geometry or AG-based codes are good choice. Considering the implementation and transplantation cost, AG-based codes are better choice, since the codes are just an extension of RS codes in some degree. The latter is now widely used in the storage industry.

To realize these ideas, we also encounter some problems as below:

a. Industry based or academic research? Since the HDD world is of great commercial interests, some of the system parameters seem hard to get, such as the real data about the jitter-like noise and the parameter of the NPML systems. What we could do is just modeling the system based on some of the papers' description, which has a potential risk that the research is useless in practical world. So maybe we could try to get close to the industry?

b. How to evaluate the error performance in such a low BER? Using a direct simulation to test the performance to such a low BER is a huge job. We're not clear if there is any effective method to evaluate the error performance.

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