Read channel for signal waveform modulation multi-level disc

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(Received 28 April 2010; revised manuscript received 4 June 2010)

A novel read channel for signal waveform modulation multi-level disc is presented in this paper. This read channel employs timing recovery system and partial response maximum likelihood detector. Compared to the previous read channel composed of level detection and run-length detection, the present read channel shows superiority in capacity increase and robust performance. Especially, relying on the partial response maximum likelihood detection, lower bit error rate can be obtained.

Keywords: multi-level disc, signal waveform modulation, read channel, partial response maximum likelihood

PACC: 4280T, 4230

1. Introduction

Optical read-only memory (ROM) has the advantage of low-cost and fast mass production. In the case of keeping the traditional readout optics and mechanism, multi-level (ML) technology based on the ROM can increase the storage capacity.[1,2]

Our team has studied some kinds of ML ROM recording,[3−6] such as the previous signal amplitude modulation (SAM) ML method. Recently, our team has developed a novel multi-level method which is called signal waveform modulation multi-level (SWM-ML) recording technology.[6−8] A sub-land/sub-pit is inserted to the original pit/land, and that makes a difference to the waveform of readout signal. SWM-ML recording is realized by using the waveform to differentiate the levels. In Fig. 1, sub-figure (a) shows the AFM photograph of SWM-ML read-only disc. Sub-figures (b) and (c) are the cross-section photographs of the places b and c in sub-figure (a), and show the sub-pit/sub-land inserted in the original land/pit.

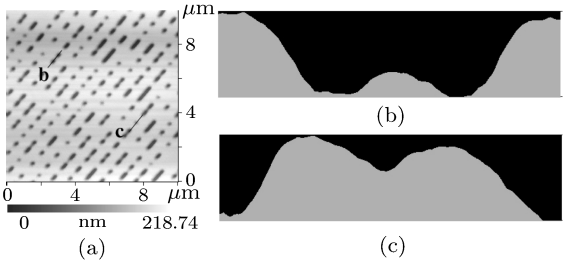


Fig. 1. AFM photograph of SWM-ML disc.

Previously, our team has proposed a simple read channel,[9] which can meet the partial requirements in SWM-ML optical disc. The previous read channel is composed of level detection and run-length detection. However, with the increase of capacity of SWM-ML optical disc, the previous read channel is inapplicable. First, with the increase of capacity of SWM-ML optical disc, the inter-symbol interference (ISI) is always increasing. But the previous read channel cannot decrease the ISI effectively. Therefore, the larger the capacity of the optical disc is, the worse the performance of the system is. Second, in the previous read channel, there are two steps to detect the ML data. The first step is detecting the run-length, and then the second step is detecting the level of this pit/land. This detection method brings out the accumulation of bit error rate (BER). It means that if the detected run-length of one pit/land is wrong, the level must be not right. Therefore, the previous read channel is inapplicable, and the novel read channel is proposed.

The novel read channel employs an interpolating timing recovery system and an improved partial response maximum likelihood (PRML) detector. The improved PRML detector is developed specially to apply in the SWM-ML optical disc. The PRML detector in the read channel could reduce the effect of ISI effectively, and the read channel would not generate the accumulation of BER. In the read channel, lower BER and more robust performance can be obtained.

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2. Proposed read channel

Figure 2 shows a block diagram of the read channel with adaptive PRML detector. In Fig. 2, radio frequency (RF) signal is input on the left. With the fixed over-sampling time, RF signal is sampled by the analogue-to-digital converter (ADC). The frequency and phase error information is sent to the interpolator. With channel timing, the interpolator interpolates sampled data. The partial response (PR) equalizer equalizes the interpolated RF signal. The target PR polynomial is {4, 9, 12, 9, 4}. The PR equalizer is a 31-taps filter impulse response (FIR) filter. The equalized RF signal is sent to the adaptive Viterbi detector. By comparing the current RF signal pattern with possible RF signal patterns which consist of reference levels, the adaptive Viterbi detector could detect SWM-ML data.

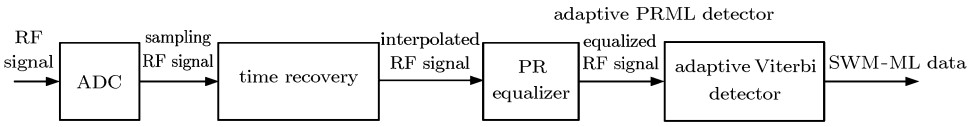


Fig. 2. Block diagram of the read channel.

2.1. Signal interpolating

In Fig. 3 an example of RF signal interpolating in the proposed read channel is presented. As shown in Fig. 3, assuming that an SWM-ML data sequence of "0, 0, 0, 1, 0, 0, 0, 0" is recorded on a disc. From the SWM-ML disc, the RF signal is readout by using the optical head and analog front end. In Fig. 3, T is the

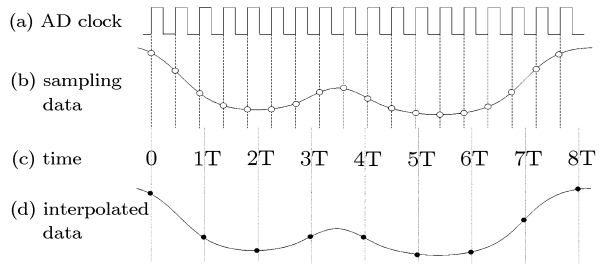


Fig. 3. Signal interpolating in proposed read channel.

period of one recorded symbol, which is referred to the channel symbol interval and reciprocal of the channel frequency. Figure 3(a) shows the oversampling clock of ADC asynchronized with channel timing. Asynchronous sampling data shown in Fig. 3(b) are obtained by sampling RF signal with the asynchronous ADC clock. In adaptive PRML detector, the data are interpolated data synchronized with channel timing, and not asynchronous sampling data. Therefore, in Fig. 3(d), the interpolator interpolates the sampling data, which can be directly used by adaptive PRML detector.

2.2. Timing recovery

The timing recovery system consists of two parts. One is the frequency detector block, and the other is the phase detector block. The function of the frequency detector block is coarse tuning, and the function of the phase detector block is fine tuning.

As shown in Fig. 4, the frequency detector block includes frequency detector and sync detector. There are 1858 channel symbols between every two sync patterns in the channel sequence. The sync detector could detect the special sync pattern consisting of 14 channel symbols pit/land. Therefore, the number of the sampling points between two sync patterns can be counted. The number of the sampling points can represent current frequency.

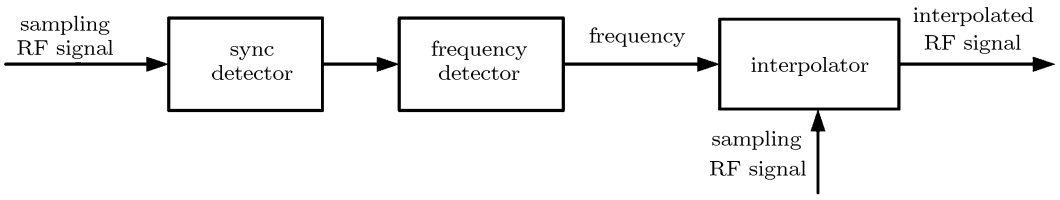


Fig. 4. Block diagram of the frequency detector.

As shown in Fig. 5, the phase detector block includes phase detector and RF generator. By looking up the adaptive table of Viterbi detector, the RF generator regenerates the reference RF signals. By comparing the regenerated RF signal with the equalized RF signal, the phase error can be detected.

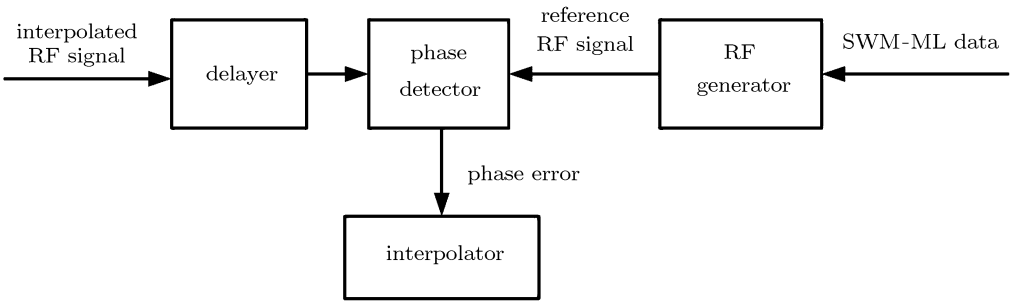


Fig. 5. Block diagram of the phase detector.

According to the calculated frequency and phase error, the interpolator can choose accurate interpolating points.

2.3. Adaptive PRML detector

The method, in which the run-length detection and level detection are separated,[10] has been already used successfully in 14 Gbyte SWM-ML read-only disc system. By using this method, the raw bit error rate (BER) can reach 10^{-4} in the 14 Gbyte SWM-ML read-only disc. However, because this method cannot decrease ISI absolutely, its performance cannot meet the requirement in 15 Gbyte SWM-ML read-only disc.

The adaptive PRML detection can effectively decrease ISI and is used in the read channel of 15-Gbyte SWM-ML read-only disc.

In the optical data storage systems, the read process is essentially linear. According to linearity, the symbol response $h(t)$ of optical discs is just the convolution of the channel sequence waveform $c(t)$ with the impulse response $f(t)$,[10] that is

$$h(t) = c(t) \otimes f(t). \tag{1}$$

The impulse response $f(t)$ of the channel is basically a temporal version of the Gaussian spot profile, just as

$$f(t) = \frac{2}{ST\sqrt{\pi}} \exp\left\{-\left(\frac{2t}{ST}\right)^2\right\}, \tag{2}$$

where T just presents the symbol spacing and S is the normalized information density of the recording channel.

We have prepared several SWM-ML read-only optical discs by adopting $(d_0, d_1, \ldots, d_i, \ldots, d_{M-1}; k)$ ML run-length limited (RLL) code.[11] Based on the experimental results, when $S = 4.6$, the impulse response is the most similar to the measured readout signals. This means that the model with $S = 4.6$ approximates the actual SWM-ML channel, thus we choose $S = 4.6$ in the PRML simulation.

It is very important to select a proper PR target polynomial in the PRML detection of ML-RLL recording channel. More than one PR mode is applicable, such as $(1+2D+2D^2+D^3)$, $(4+9D+12D^2+9D^3+4D^4)$, $(1+2D+3D^2+3D^3+2D^4+D^5)$. The spectrum of the SWM-ML channel can be obtained from the real SWM-ML RF signal (see Fig. 6). This figure also shows all frequency responses of the RF modes mentioned. It is clearly seen from the figure that $(4+9D+12D^2+9D^3+4D^4)$ and $(1+2D+3D^2+3D^3+2D^4+D^5)$ PR mode are closer to the spectrum of the SWM-ML channel, thus these two PR targets may have better performances than others. This presents two issues. One is that it is easy to equalize SWM-ML channels into the mode. The other is that the magnitude of RF sampling signal after PR equalization is closer to the PR target. However, the proper PR mode is not only the closer one to the spectrum of the SWM-ML, but also is easier to be realized. The $(4+9D+12D^2+9D^3+4D^4)$ PR mode is close enough to the spectrum of the SWM-ML channel, and is easy to be realized. Therefore, in order to reduce the complexity of the system, we adopted $(4+9D+12D^2+9D^3+4D^4)$ PR mode.

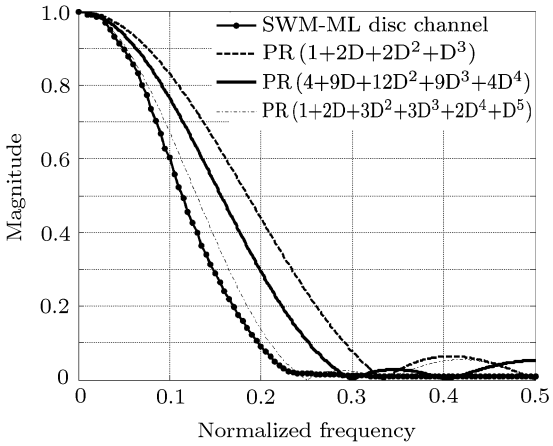


Fig. 6. The spectrum of real RF signals from SWM-ML read-only disc and the frequency response of several partial response modes.

In a PRML system, the channel is truncated to a target PR by linear equalization. Then, maximum likelihood sequence detection using the Viterbi algorithm is applied to this equalized sequence.

Figure 7 shows the Trellis diagram of the PRML system using $(4+9D+12D^2+9D^3+4D^4)$ PR mode with $(d_0,\ d_1,\ \ldots,\ d_i,\ \ldots,\ d_{M-1};\ k)$ ML-RLL code, where a_k and z_k denote the k-th recorded datum and the corresponding equalized output, respectively. If we choose $(4+9D+12D^2+9D^3+4D^4)$ PR mode as a target PR, the number of states in the Trellis diagram is 16 (2^4=16). In this system, however, the effect of the RLL (0, 10) modulation code must be considered, and the states of "0, 1, 0, 1" and "1, 0, 1, 0" are not allowed to appear. Therefore, the numbers of states are 14.

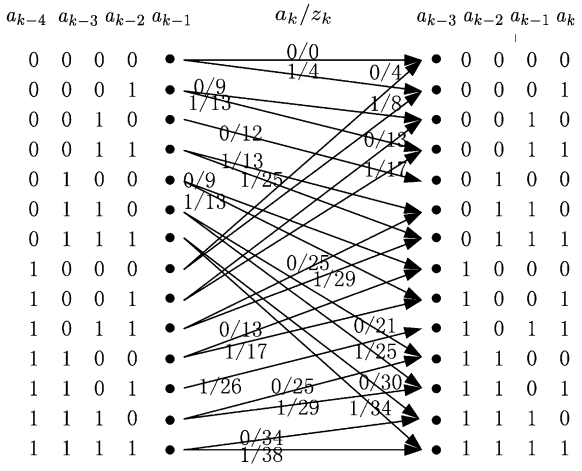


Fig. 7. Trellis diagram for PR $(4+9D+12D^2+9D^3+4D^4)$ under the condition of RLL with $(d_0,\ d_1,\ \ldots,\ d_i,\ \ldots,\ d_{M-1};\ k)$ ML-RLL code. "a_k/z_k" represents input/output. $a_k = \{0, 1\}$ is the input, and z_k is the target signal of the PR channel output in the current state.

Figure 7 clearly shows that z_k is determined not only by a_k but also by a_{k-1}, a_{k-2} and a_{k-3}. That is to say, controlled ISI is added by using $(4+9D+12D^2+9D^3+4D^4)$ PR mode as the target PR.

3. Experimental results

Based on a commercial DVD player, our team set up the optical readout system. We reserved all the optical and mechanical units. In the whole readout system, we use a digital signal processor (DSP) and a field programmable gate array (FPGA) chip to control servo, such as focusing and tracking, and implement SWM-ML read channel system. The system clock is 100 MHz. In order to evaluate the read channel system, we process these readout data.

Because it is hard to obtaining a wide range of SNR from the optical readout system, we simulated to obtain the BER performance curves, as shown in Fig. 8. In the real optical readout system, the BER of 10^{-4} is obtained at an SNR of about 25 dB. It matches with the simulated result. Then, in the readout system, the BER can achieve below 10^{-5} even when the Optical Pickup Unit (OPU) has a serious tilt.

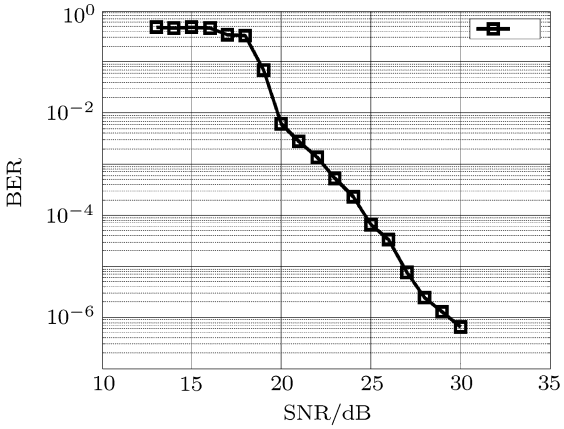


Fig. 8. The BER performance.

4. Conclusion

We proposed an SWM-ML read channel, consisting of a timing recovery system and an adaptive PRML detector. An adaptive Viterbi detector, which utilizes every RF data to adjust the reference levels to calculate branch metrics, is used in the adaptive PRML detection system. By the adaptive PRML detector, the read channel system is more robust. The effect of ISI and BER is also decreased. We implemented the novel read channel system using a DSP and an FPGA chip. The experimental results show a good performance. The BER can achieve below 10^{-5} even when the OPU has a serious tilt.

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