Improved partial response maximum likelihood method combining modulation code for signal waveform modulation multi-level disc*

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(Received 26 January 2014; revised manuscript received 17 March 2014; published online 10 August 2014)

In this paper, we describe an improved adaptive partial response maximum likelihood (PRML) method combining modulation code for signal waveform modulation multi-level disc. This improved adaptive PRML method employs partial response equalizer and adaptive viterbi detector combining modulation code. Compared with the traditional adaptive PRML detector, the improved PRML detector additionally employs illogical sequence detector and corrector. Illogical sequence detector and corrector can avoid the appearance of illogical sequences effectively, which do not follow the law of modulation code for signal waveform modulation multi-level disc, and obtain the correct sequences. We implement the improved PRML detector using a DSP and an FPGA chip. The experimental results show good performance. The higher efficient and lower complexity can be obtained by using the improved PRML method than by using the previous PRML method. Meanwhile, resource utilization of the improved PRML detector is not changed, but the bit error rate (BER) is reduced by more than 20%.

Keywords: multi-level disc, signal waveform modulation, viterbi detector, partial response maximum likelihood

PACS: 42.79.Vb **DOI:** 10.1088/1674-1056/23/10/104217

1. Introduction

Multi-level (ML) optical storage technology is an important way to increase the storage density of the optical disc. Many kinds of ML optical storage technologies have been developed during the past few years.[1–5] Our team has proposed a novel ML method called signal waveform modulation (SWM) recording technology.[6–8] This kind of SWM ML read-only disc can be manufactured on the common disc manufacturing line. By using the same production technology, the SWM ML disc can increase the storage density significantly.

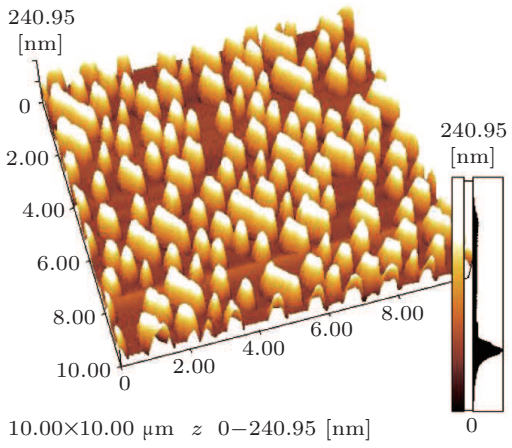


Fig. 1. (color online) AFM photograph of SWM ML disc.

Figure 1 shows an atomic force microscopy (AFM) image of the SWM ML read-only disc. ML is realized by different record mark microstructures in the SWM ML disc. A sub-land/sub-pit is inserted into the original pit/land, which makes a different waveform of readout signal as shown in Fig. 2. The different kinds of signal waveforms can be generated by inserting the sub-lands/pits at different positions. The different kinds of signal waveforms indicate different levels. To obtain higher code rate and increase the storage density of the optical disc, a new bimodulation code is proposed for the SWM ML disc.[9,10]

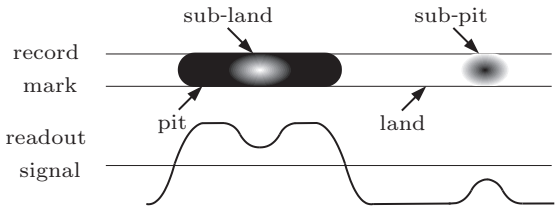


Fig. 2. Record marks and readout signal of SWM ML disc.

The equalization and detection technology for the SWM ML discs is a key technology. Our team has proposed a simple method to detect the readout signal of the SWM ML discs,[11] which can meet the partial requirements. This kind of detection method is composed of level detection and run-length detection. However, with increasing the storage capacity of the SWM ML discs, this kind of detection method is not applicable. After that, our team used the traditional partial response maximum likelihood (PRML) detection in the

*Project supported by the National Natural Science Foundation of China (Grant No. 61127010).

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SWM ML discs.[12] Compared to the previous level detection and run-length detection method, traditional PRML detection could reduce the inter-symbol interference effectively. Though traditional PRML detection can be used in the SWM discs, because of some unique characteristics of the SWM discs, the result of PRML detection for the SWM ML discs is not good enough. Therefore, it is not suitable to apply PRML method to SWM ML discs directly, and according to the unique characteristic of the SWM ML discs, an improved PRML detection is proposed. On the basis of the traditional PRML detector, the improved PRML detector employs partial response equalizer and adaptive viterbi detector combining modulation code. In the adaptive viterbi detector, illogical sequence detector and corrector are employed additionally, which is combined with modulation code, in order to avoid effectively the illogical sequences that violate the modulation code for the SWM ML disc. The improved PRML detection combining modulation code is realized on the commercially-available disc production equipment and readout system, and lower bit error rate (BER) and more robust performance is obtained.

2. Improved PRML method combining modulation code

2.1. Modulation code and error type for SWM ML disc

In order to obtain lower BER, we analyze the error type for SWM ML disc. The error type consists of shift and loss of sub-pit/sub-land and illogical sequence. Shift and loss of sub-pit/sub-land is due to manufacture error of optical disc, spot on the optical disc or characteristic limit of optical head. This kind of error type cannot be corrected, because the input real RF signal fails to respond to the ideal signal waveform of data sequence recorded on the disc.

The other kind of error type is illogical sequence, which is related to characteristics of PRML method and modulation code for SWM ML disc. This kind of error type could be corrected. Illogical sequence appears in many forms. Figure 3 shows three main kinds of illogical sequences for SWM ML disc. In all the three panels, the top sequence represents the right data, which complies with the law of code modulation, the middle sequence represents the wrong data, which does not comply with the law of code modulation, called illogical sequence, and the two curves at the bottom represent the ideal signal waveforms: one is for the right data and the other is for wrong data. The dotted line represents the ideal signal waveform for the wrong data, and the solid line denotes the ideal signal waveform for the right data. As shown in Fig. 3(a), there are two sub-pits in the same run-length. According to code modulation, in one run-length, more than one sub-pit/land is not allowed to appear. As shown in Fig. 3(b), there are continuous sub-pit and sub-land. According to code modulation, continuous sub-pit/land is not allowed to appear. As shown in Fig. 3(c), there are continuous three 2T run-lengths. According to code modulation, continuous three 2T is not allowed to appear.

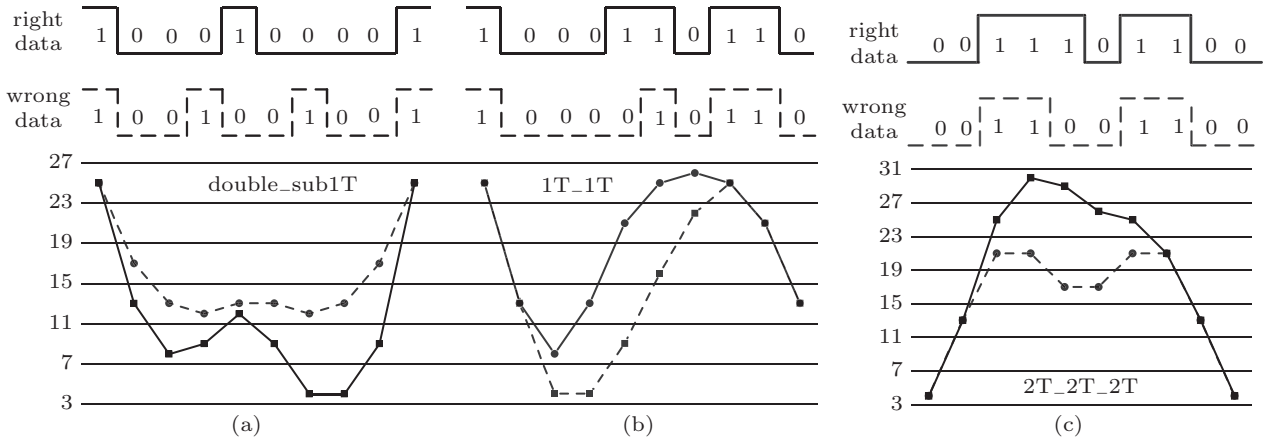


Fig. 3. Error types of SWM ML disc.

Table 1 shows modulated run-lengths and levels. Level 0 of all the run-lengths is their origin waveform, meaning there is no sub-pit/land. There is more than one level from 5T to 11T. In SWM ML disc, only 1T could be inserted in the origin run-length as the sub-pit/land. By inserting the sub-lands/pits at the different positions, the different levels are generated. In Table 1, the three numbers represent an inserted position of the 1T sub-pit/land in a different level and run-length. For example, in the level 1 of 9T, the three numbers, '216', represent that the distance between the 1T sub-pit/land and the left edge of 9T is 2T, and the distance between the 1T sub-pit/land and the right edge of 9T is 6T. The three numbers, '216', can be considered as three sub run-lengths, 2T, 1T, and 6T, which constitute the whole run-length, 9T. Different sub run-lengths combinations form different levels.

Table 1. Modulated run-lengths and levels.

Run-length	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
5T	212						
6T	213	312					
7T	214	313	412				
8T	215	314	413	512			
9T	216	315	414	513	612		
10T	217	316	415	514	613	712	
11T	218	317	416	515	614	713	812

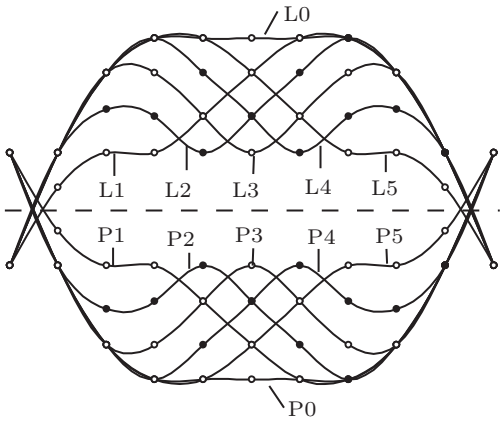


Fig. 4. Readout signal waveforms of different levels for 9T.

Table 2. Six kinds of data sequences in the run-length of 9T.

Level	Data sequence	Run-length
0	11 000000000 11	
1	11 001000000 11	216
2	11 000100000 11	315
3	11 000010000 11	414
4	11 000001000 11	513
5	11 000000100 11	612

In order to explain the appearance of the illogical sequences, we take the run-length of 9T for example. For the run-length of 9T, there are six levels as shown in Fig. 4. In the run-length of 9T, according to the modulation code, only six kinds of the data sequences are logical, which are shown in Table 2. Table 2 shows the data sequences and sub run-length combinations of all levels, which are corresponding to all levels of 9T run-length in Table 1. For example, level 1 of 9T run-length is corresponding to data sequence '11 001000000 11', which is combined with 2T, 1T, and 6T, expressed as '216'. However, according to the normal PRML method, there may be some illogical sequences in the resulting data, such as two sub-pits in one run-length '11 001000100 11' and continuous two 1T '11 000000010 11'. According to the characteristics of PRML method, paths could be set in advance and illogical paths can be removed. For example, suppose that the length of target PR mode is 5 and modulation code is just as that in Table 1. The length of each path equals that of target PR mode. Then illogical paths, containing (0, 0, 1, 0, 1), (0, 1, 0, 1, 0), (0, 1, 0, 1, 1), (1, 0, 1, 0, 0), (1, 1, 0, 1, 0), and (1, 0, 1, 0, 1), can be removed. Only the illogical sequences, the length of which is not longer than that of PR mode, can be removed. For the run-length of 9T, some illogical sequences, the length of which is longer than that of PR mode, may appear, such as (0, 0, 1, 0, 0, 0, 1, 0, 0).

Because the length of target PR mode is limited, illogical sequence appears. Then, by increasing the length of target PR mode, illogical sequence can be avoided. But because increasing the length of target PR mode could seriously increase the resource utilization of viterbi detector in the whole hardware system of read channel, this approach does not work.

Resource utilization of viterbi detector in the whole hardware system of read channel depends on complexity of viterbi detector. According to the principle of PRML method, complexity of viterbi detector is sensitive to the number of logical paths. The number of logical paths, N_{p}, depends on the length of PR mode and the number of illogical paths, just as

$$N_{\mathrm{p}} = 2^{l-1} - M_i, \tag{1}$$

where l is the length of PR mode, and M_i is the number of illogical paths.

Table 3. Numbers of logical and illogical paths for different lengths of PR.

Length of PR	Number of illogical paths	Number of logical paths
4	2	14
5	6	26
6	18	46
7	46	82

As shown in Table 3, with increasing the length of PR mode, the number of logical paths almost increases exponentially. Meanwhile, resource utilization of viterbi detector in the whole hardware system of read channel increases linearly with the number of logical paths. In commercially-available disc hardware system, when the length of PR mode is 5, resource utilization of the whole read channel is 81% and that of viterbi detector is 20%. Longer PR mode cannot be realized in commercially-available disc hardware system, and only can be in a more expensive hard system. Therefore, illogical sequence can be avoided by increasing the length of PR mode,

but resource efficiency is lower and complexity of viterbi detector is higher.

In order to solve this problem, the PRML method is improved by combining the modulation code.

2.2. Improved PRML detection combining modulation code

Figure 5 shows the block diagram of the improved PRML detector. In Fig. 5, radio frequency (RF) signal is input from the left. The partial response (PR) equalizer equalizes the RF signal. The target PR mode is $\{4, 9, 12, 9, 4\}$. The PR equalizer is a 31-tap 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 achieve pre-data. The pre-data are sent to the illogical sequence detector. The function of the illogical sequence detector is to sort out the illogical sequences from the pre-data. The illogical sequences are sent to a corrector. The function of the corrector is to correct the illogical sequence into the logical sequences. Based on the pre-data and the corrected data, the SWM ML data are output. The improved viterbi detector in the dashed frame consists of viterbi detector, illogical sequence detector, and corrector.

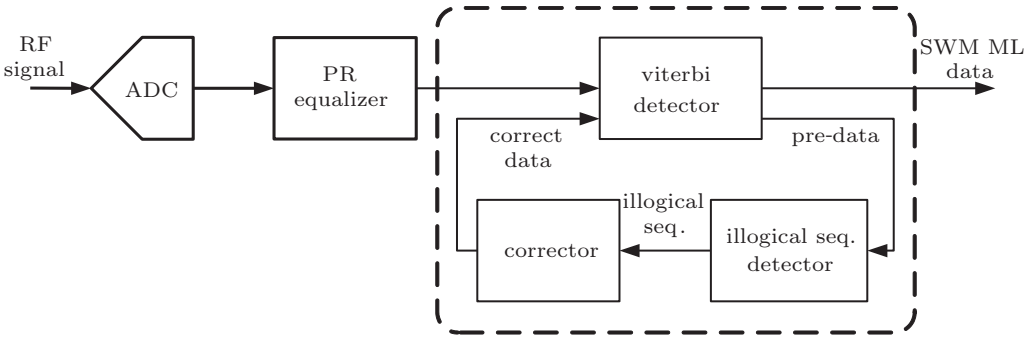


Fig. 5. Block diagram of improved PRML detector.

2.3. Improved viterbi detector

As shown in Fig. 6, the improved viterbi detector is composed of branch metric calculator, add compare select, path metric memory, path memory, and reference level feedback. The $\mathrm{RF_{eq}}$ signal is sent to branch metric calculator (BMC) to calculate the branch metric (BM). The BM of the state $(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ is expressed as

$$\begin{aligned} &\mathrm{BM}_k(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k) \\ &= \left[\mathrm{RF}_k - r(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)\right]^2, \end{aligned} \tag{2}$$

where a_k is the data sequence recorded on the optical disc, $r(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ is the reference level of state $(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$, r_i is the convolution of the state sequence $(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$, and the PR mode parameters are

$$r(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k) = \sum_{m=0}^{M-1} a_{k-m} p_m, \tag{3}$$

with p_m $(0 \le m \le M)$ being the PR mode parameters.

The common add-compare-select (ACS) unit is composed of three operations, adding, comparing, and selecting. The operation of adding is accumulating Euclidian distance $\mathrm{BM}_k(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ between sequence $r(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ and RF_k to obtain the path metric (PM), just as

$$\begin{aligned} &\mathrm{PM}(a_{k-3}, a_{k-2}, a_{k-1}, a_k) \\ &= \mathrm{PM}(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}) \\ &\quad + \mathrm{BM}(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}) \\ &= \sum_{j=0}^{k} \left[\mathrm{RF}_k - r(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1}, a_k)\right]^2. \end{aligned} \tag{4}$$

The operation of comparing and selecting is to compare $\mathrm{PM}(a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ of all the paths that end the same state $(a_{k-3}, a_{k-2}, a_{k-1}, a_k)$, and only the path with minimum $\mathrm{PM}(a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ can survive.

In order to correct the illogical sequences, the illogical sequence detector and corrector are added to the common ACS. The survived path from the operation of comparing and selecting is sent to the illogical sequence detector. Illogical sequence detector sorts out illogical sequences from the survived path. The survived path containing illogical sequences is corrected by corrector. The corrected survived path and $\mathrm{PM}(a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ can be achieved.

The corrected paths are sent to path memory, which provides the path in last time to ACS. From path memory, SWM ML data can be obtained. The corrected $\mathrm{PM}(a_{k-3}, a_{k-2}, a_{k-1}, a_k)$ are sent to path metric memory, which provides $\mathrm{PM}(a_{k-4}, a_{k-3}, a_{k-2}, a_{k-1})$ for ACS. Meanwhile, the block of reference level feedback can provide the adaptive reference level for BMC.

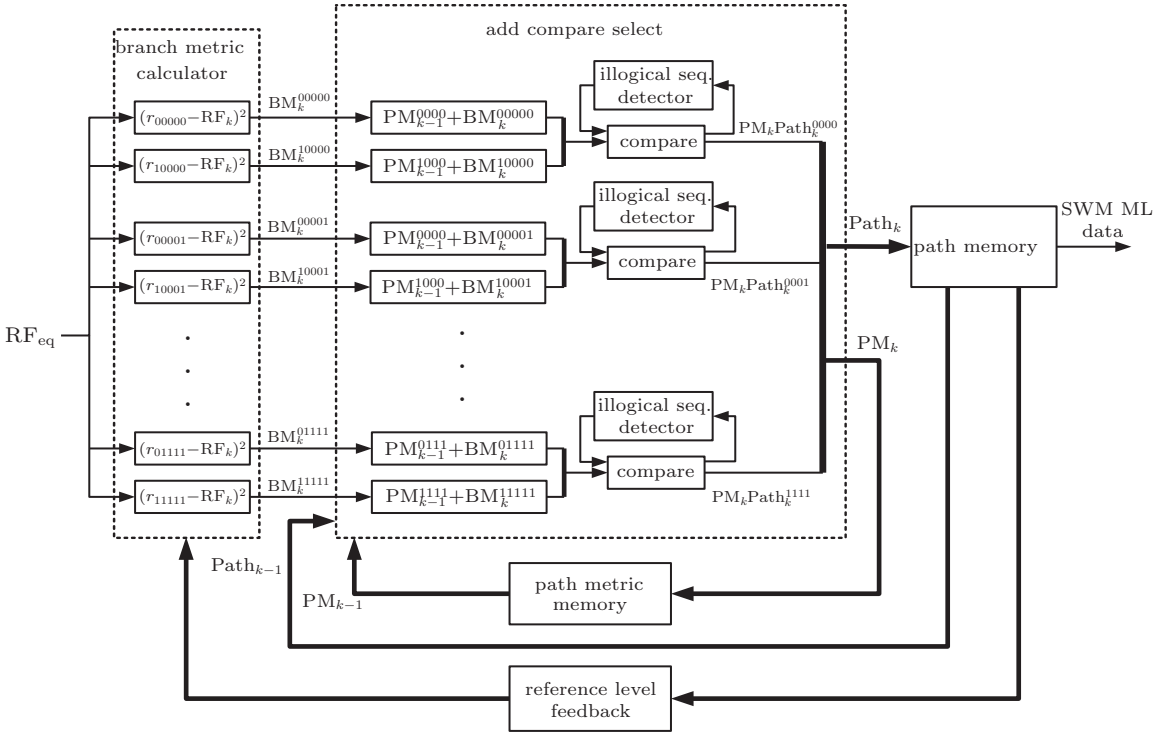


Fig. 6. Block diagram of improved viterbi detector.

Figure 7 shows the trellis diagram of the viterbi detector by using PR {4, 9, 12, 9, 4} mode. Because the states of '0, 1, 0, 1' and '1, 0, 1, 0' are not allowed to appear, there are 14 states in the trellis diagram. Between one state and the next state, each branch is connected by a line. The left state represents the current state, and the right one represents the next state.

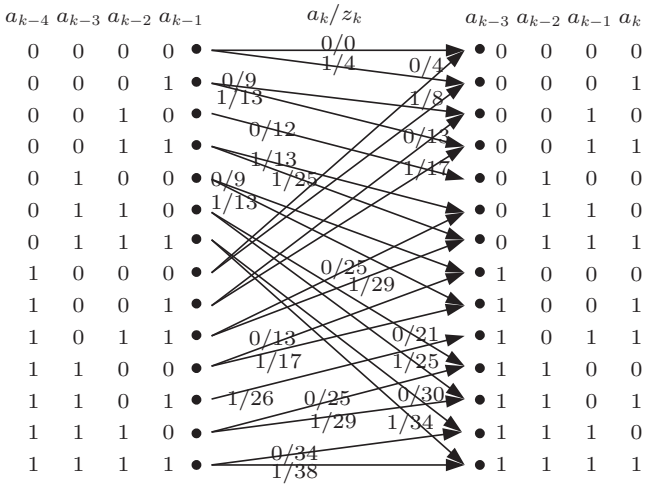


Fig. 7. Trellis diagram for PR (4 9 12 9 4) mode in the viterbi detector.

2.4. Illogical sequence detector and corrector

In order to correct the illogical sequences, the illogical sequence detector and corrector are added to the common ACS, as shown in Fig. 8. Take ending state (0, 0, 0, 0) for example. By comparing $\mathrm{PM}_{k-1}^{0000}+\mathrm{BM}_k^{00000}$ with $\mathrm{PM}_{k-1}^{1000}+\mathrm{BM}_k^{10000}$, the survived path with minimum $\mathrm{PM}(a_{k-3},a_{k-2},a_{k-1},a_k)$ can be obtained. Suppose that $\mathrm{PM}_{k-1}^{0000}+\mathrm{BM}_k^{00000}$ is smaller, then the survived path will be $\mathrm{Path}_k^{0000}=(\mathrm{Path}_{k-1}^{0000},a_k=0)$. Path_k^{0000} is sent to illogical sequence detector to detect whether there are illogical sequences. If there are illogical sequences in Path_k^{0000}, combining the feedback of Path_{k-1} and PM_{k-1}, the corrector can obtain the corrected $\mathrm{Path}_k'^{0000}$ and $\mathrm{PM}_k'^{0000}$.

Take ending state (0, 0, 0, 0) for example. Figure 9 shows the block diagram of the illogical detector and corrector. The final result is corrected $(\mathrm{PM}_k',\mathrm{Path}_k)'^{00000}$. For multiplexer MUX 1, control signal is comparing result between the survived Path_k^{0000} and illogical sequence table, output signal is $(\mathrm{PM}_k',\mathrm{Path}_k)'^{00000}$ and input signals are $(\mathrm{PM}_k,\mathrm{Path}_k)^{00000}$ and output signal of MUX 2. If the survived $(\mathrm{PM}_k,\mathrm{Path}_k)^{00000}$ is logical sequence, MUX 1 outputs $(\mathrm{PM}_k,\mathrm{Path}_k)^{00000}$, and if not so, MUX 1 outputs the output signal of MUX 2. For MUX 2, control signal is compared with the result between the last five bits (1, 0, 0, 0, 0) of un-survived path $(\mathrm{Path}_{k-1}^{1000},a_k)$ with larger $\mathrm{PM}_{k-1}^{1000}+\mathrm{BM}_k^{10000}$ and illogical sequence table, the output signal is sent to MUX 1 and input signals $(\mathrm{PM}_k^{+}\max,\mathrm{Path}_k)^{00000}$ and $(\mathrm{Path}_{k-1}+\text{'0'},\ \mathrm{PM}_{k-1}+\mathrm{BM}_k^{10000})^{1000}$ survive. If the last five bits of un-survived path $(\mathrm{Path}_{k-1}^{1000},a_k)$ are an illogical sequence, MUX 2 outputs survived Path_k^{0000} and maximum value is assigned to PM_k^{0000}. If the last five bits of un-survived path $(\mathrm{Path}_{k-1}^{1000},a_k)$ is a logical sequence, MUX 2 outputs un-survived path $(\mathrm{Path}_{k-1}^{1000},a_k)$ and its PM $\mathrm{PM}_{k-1}^{1000}+\mathrm{BM}_k^{10000}$.

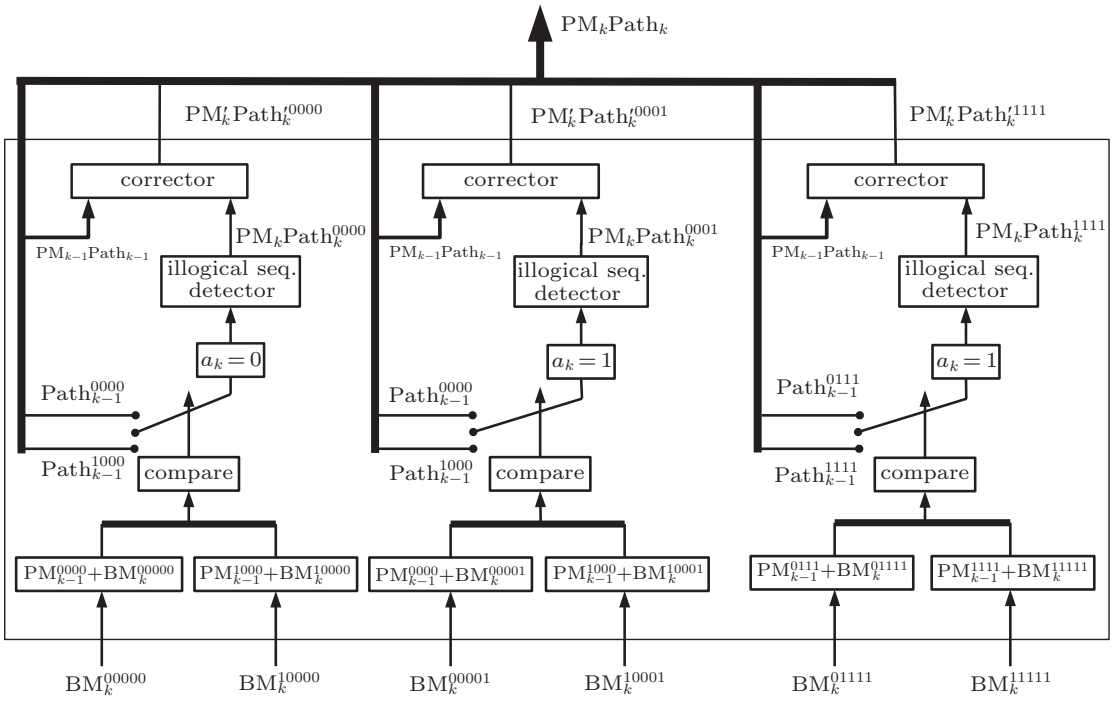


Fig. 8. Block diagram of add compare select.

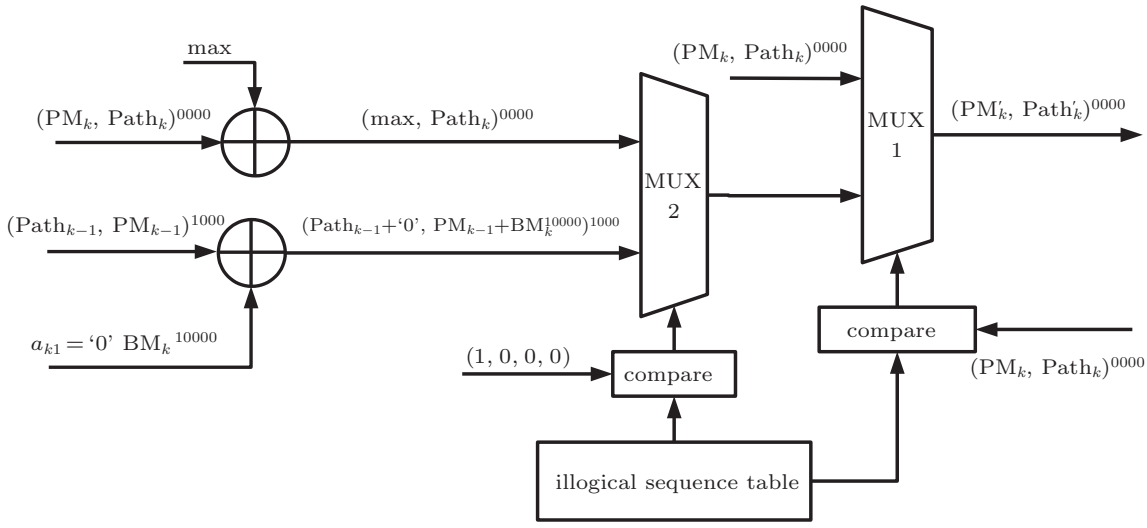


Fig. 9. Block diagram of the illogical detector and corrector.

3. Experimental results

To validate the improved PRML method, our team set up an optical readout system on a standard DVD driver. In the whole readout system, we use a digital signal processor (DSP) and a field programmable gate array (FPGA) chip to implement the improved PRML detection of the SWM ML disc.

In Fig. 10, BERs of the same data blocks using the traditional and improved PRML methods are shown. A unit on the horizontal axis represents a data block and there are 14 data blocks in total. One data block consists of 10 error correction code (ECC) blocks. One ECC block consists of 16 sectors. One sector consists of 13 recording frames. In Fig. 10, BERs are shown by using the traditional and improved PRML methods. Using the improved PRML method, the lower BER can be obtained.

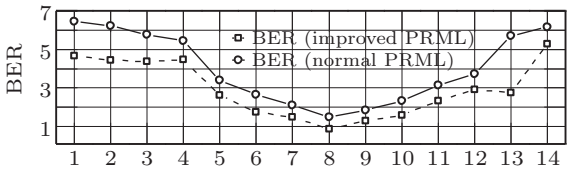


Fig. 10. BER performance.

Table 4. Error bit types and proportions for SWM ML disc.

Error bit types	Proportion
1T shift	50%–60%
Illogical sequence	30%–40%
1T loss	10%

Table 4 shows error bit types and proportion for SWM ML disc. The proportion is calculated by 140 ECC blocks. In SWM ML disc, there are three kinds of error types, including 1T shift, 1T loss, and illogical sequence.

The cause of error bit types '1T loss' and '1T shift' is that the waveform of wrong data is similar to that of right data. The two kinds of error types are related to characteristics of optical head, and difficult to remove.

The illogical sequences, related to characteristics of PRML method and modulation code for SWM ML disc, could be corrected by using improved PRML method. In the experiment based on 140 ECC blocks, almost all the illogical sequences are corrected and BER is reduced by 30%. Based on the traditional PRML detector, only additional illogical sequence detector and corrector are added into the improved PRML detector. Illogical sequence detector and corrector only work on illogical sequences and not on logical sequences.

4. Conclusion

We proposed a PRML method combining modulation code for the SWM ML disc. The improved PRML method employs partial response equalizer and adaptive viterbi detector combining modulation code. Besides the traditional adaptive PRML detector, the improved PRML detector employs illogical sequence detector and corrector additionally. Illogical sequence detector and corrector can avoid the appearance of those illogical sequences effectively and obtain the correct sequences. We implement the improved PRML detector using a DSP and an FPGA chip. The experimental results show good performance. Using the improved PRML method, higher efficient and lower complexity can be obtained. The resource utilization of the improved PRML detector is not changed compared with that of the previous PRML detector, but BER is reduced by more than 20%.

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