Blind Decision Feedback Equalizer for Holographic Versatile Disc

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Abstract: As the amount of data increases, holographic data storage (HDS) is considered as a next generation storage medium. Since HDS uses two-dimensional (2D) data, it causes intersymbol interference (ISI) between adjacent pixels not only in the horizontal direction but also in the vertical direction. Thus, studies have been carried out to reduce such 2D ISI, and especially many researches using the partial response maximum likelihood (PRML) method have been carried out. These PRML methods have good bit-error-rate (BER) performance, but also have various disadvantages. Therefore, we propose a simple blind decision feedback equalizer (blind DFE) that does not use soft output Viterbi algorithm (SOVA) for application to European standard holographic versatile disc (HVD). First, we propose a blind equalizer using simle theshold method to get information that the equalizer can refer to. In order to make it work well in any environment, the threshold value is adaptively determined using the statistical characteristics of the received image. And, in order to reduce errors due to the data that cannot be distinguished only by the blind equalizer, we add a decision feedback loop after the blind equalizer. Finally, various simulations were conducted to confirm the performance of blind DFE for HVD.

1 INTRODUCTION

As the amount of data increases, holographic data storage (HDS) is considered as a next generation storage medium. Unlike other optical disks, HDS uses holographic images to store two-dimensional (2D) data pages on a holographic versatile disc (HVD). The European standard for HVD was proposed in 2007 (ECMA, 2007a; ECMA, 2007b).

Since HDS uses 2D data, it causes intersymbol interference (ISI) between adjacent pixels not only in the horizontal direction but also in the vertical direction. This 2D ISI has a lot of impact on the performance of HDS, and many studies are going on to reduce it. The most studied methods to reduce 2D ISI in HDS is the partial response maximum likelihood (PRML) method using soft output Viterbi algorithm (SOVA) (Kim and Lee, 2009; Koo et al., 2012; Koo et al., 2013; Koo et al., 2014). These PRML methods have good bit-error-rate (BER) performance, but also have various disadvantages.

There are a few problems that arise from the use of SOVA. In order to improve BER performance, the PRML methods use SOVA (Hagenauer and Hoeher, 1989) based on Viterbi decoder (Viterbi, 1967) as maximum likelihood (ML) method. The first problem is that this Viterbi algorithm requires a lot of computation because all Viterbi paths need to be investigated. Especially, since the Viterbi algorithm needs to be applied in two dimensions in order to apply it to the HDS, much more computational complexity is required than the Viterbi decoder used in the field of communications. In (Koo et al., 2012; Koo et al., 2013; Koo et al., 2014), many studies have been done to reduce the computational complexity of 2D SOVA while improving performance, but it is still a problem to have a large amount of computation as SOVA is used.

The second problem that arises from using 2D SOVA is that it does not work with European standard code. In the European standard, in order to reduce the error rate of a symbol, if a certain pixel has a value of 1, the adjacent pixels can not have a value of 1 in a 4-by-4 (4×4) symbol. That is, only three pixels of the sixteen pixels have a value of one and the remaining pixels have a zero value. However, the Viterbi decoder basically assumes that all messages are equally probable (Viterbi, 1967). Therefore, if the European standard code is used, SOVA will not work properly because the probability of 0 and 1 is different.

The last problem with using the PRML method is that a training sequence is necessary. Using training

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sequences can not make use of that much data, and because the equlizer is trained to a specific environment, performance degrades when the environment changes. Therefore, in order to increase the data rate and robustness to various environments, blind equalizer that do not require training sequences have to be developed and used as in the field of communications. However, since the PRML method uses a training equalizer that requires a training sequence, the data rate is lowered, and when the channel environment is changed, the performance may be degraded.

Therefore, we propose a simple blind equalizer that does not use SOVA for application to European standard HVD. The remaining paper is organized as follows. Section 2 explains the background HVD channel model, and a simple form of blind eualizer is proposed in Section 3. In order to compensate for the performance of the blind equalizer, Section 4 describes a decision feedback equalizer (DFE), and several simulation results will be represented in Section 5. Finally, we will conclude and discuss the results in Section 6.

2 HVD CHANNEL MODEL

In HVD, using spatial light modulator (SLM), the input data page, $d[x,y]$, is encoded to the holographic medium along the reference laser beam (Vadde and Kumar, 1999). When reading the stored data page, the data page is displayed in the form of a hologram using the same reference beam and read by a charge-coupled device (CCD). In this process, the data page suffers blur effect (2D ISI), noise and misalignment. In this channel environment, blur effect and misalignment are modelled as point spread function (PSF) and noise is modelled as additive white Gaussian noise (AWGN) (Vadde and Kumar, 1999; Keskinoz and Kumar, 2000).

The continuous PSF is expressed by

$$h(x,y) = \frac{A^2}{\sigma_b^2}\operatorname{sinc}^2\left(\frac{x-m_x}{\sigma_b}, \frac{y-m_y}{\sigma_b}\right) \qquad (1)$$

where A is the signal amplifier, σ_b is the blur grade, and m_x and m_y are the misalignments in the horizontal and vertical directions, respectively. In this paper A is set to $\sqrt{2}$. And the discrete PSF is given by

$$h[x,y] = \int_{y-\frac{\alpha}{2}}^{y+\frac{\alpha}{2}} \int_{x-\frac{\alpha}{2}}^{x+\frac{\alpha}{2}} h(x',y')dx'dy' \qquad (2)$$

where $\alpha(0 < \alpha \leq 1)$ is a linear fill factor of the CCD pixels. In this paper, we used 1 as α.

As mentioned earlier, channel noise $n[x,y]$ is modelled as AWGN. And the channel signal-to-noise ratio (SNR) is defined as follows:

$$\mathrm{SNR} = 10\log_{10}\left(\frac{1}{\sigma_w^2}\right) \qquad (3)$$

where σ_w^2 is the AWGN power.

Therefore, the image detected by the CCD sensor $r[x,y]$ is obtained as follows:

$$r[x,y] = d[x,y] \otimes h[x,y] + n[x,y] \qquad (4)$$

where $\otimes$ is a 2D convolution operator. Figure 1 shows the block diagram of this channel model.

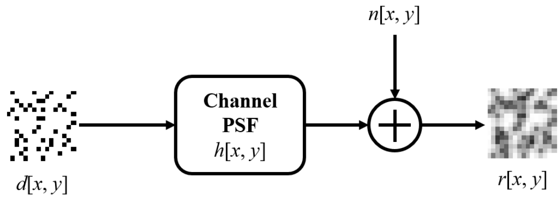


Figure 1: Block diagram of channel model.

3 BLIND EQUALIZER

The image obtained by the CCD sensor passes through a 2D equalizer to eliminate the 2D ISI, and the equalizer output $z[x,y]$ is as follows:

$$z[x,y] = r[x,y] \otimes C[x,y] \qquad (5)$$

where $C[x,y]$ is the array of equalizer coefficient which are adaptively updated using the error.

Figure 2 represents the structure of a conventional 2D training equalizer. When the training sequence is used in the PRML method, the sequence passes through partial response (PR) target to perform encoding for the ML scheme.

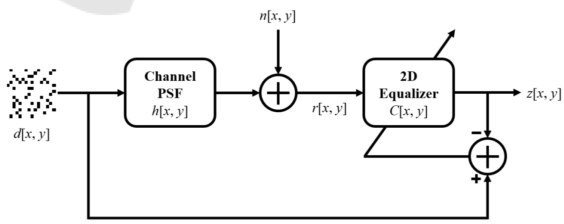


Figure 2: Structure of conventional 2D equalizer.

As mentioned earlier, the use of training equalizer reduces the data rate because it requires a training sequence, and because it is trained to a specific environment, it becomes vulnerable to various environmental changes. Thus, it is necessary to develop and use a blind equalizer. However, the blind equalizers used in the field of communications, such as constant modulus algorithm (CMA) (Sato, 1975) and multi-modulus algorithm (Yang et al., 2002), are not applicable to

HVD. This is because the blind equalizers in the field of communications match the norm of complex symbol to a specific value, but the data of HVD is composed of binary pixel arrays. Therefore, we propose a simple blind equalizer for HVD which has a different mechanism from that in the field of communications.

Although it is not possible to match the equalizer output to a specific value as in the field of communications, some information from the received image is necessary to update the equalizer. So we used simple threshold method to get information that the equalizer can refer to. Figure 3 depicts the structure of proposed blind equalizer.

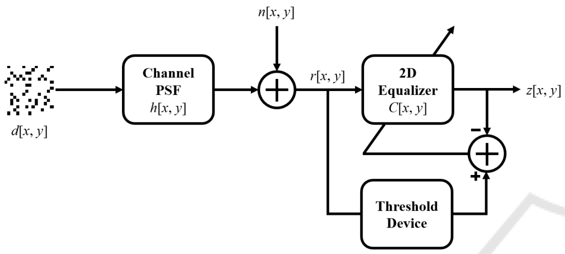
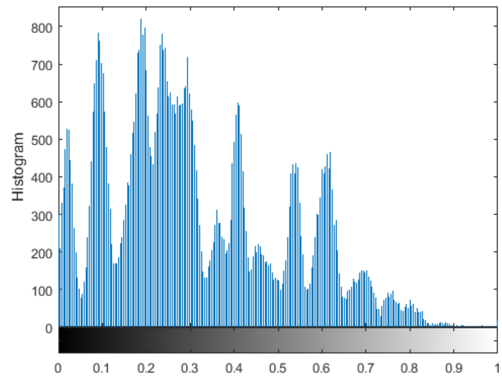


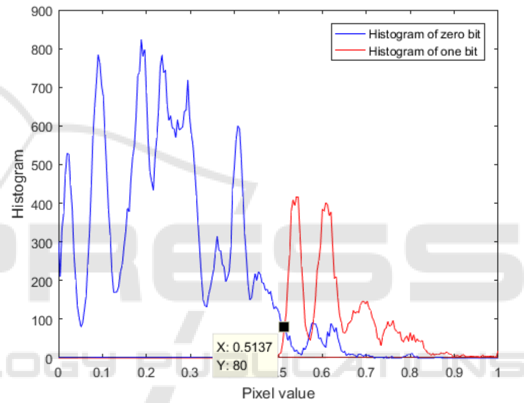
Figure 3: Structure of proposed blind equalizer.

To make the threshold method work well, it is important to set the threshold value well. Thus, in order to make it work well in any environment, the threshold value is adaptively determined using the statistical characteristics of the received image, not simply using the mean value.

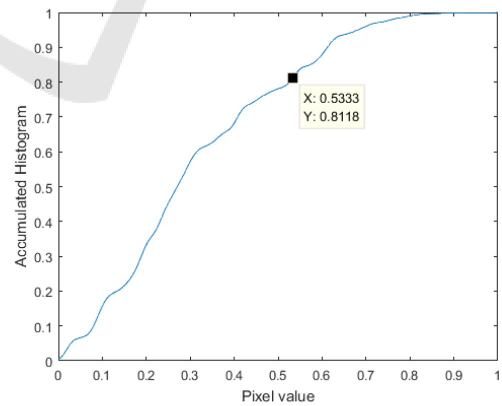
Figure 4 shows the statistical characteristics of the received images when using the European standard. Figure 4 (a) represents the histogram of total received image, and dividing this into a 0-bit histogram and 1-bit histogram, the results graph is shown in Figure 4 (b). From this graph, we can determine which value should be set to the threshold value to distinguish between 0 and 1 well. (In this case, the pixel value of 0.5137 is set as the threshold value because it can distinguish between 0 and 1 well.) Figure 4 (c) depicts accumulative histogram of total received image. In the European standard, since there are 13 zeros in one symbol, it can be seen that 0 and 1 can be distinguished by setting the pixel value having the value corresponding to 13/16 in the accumulative histogram as the threshold value. In this case, the pixel value of 0.5333 having the accumulative histogram value of 0.8118 closest to 0.8125 corresponding to 13/16 in the accumulative histogram is set as the threshold value. This threshold value is good enough to distinguish between 0 and 1 in the present environment. Using this scheme, it is possible to find the optimal threshold value to distinguish between 0 and 1, even if the statistical characteristics of the received image change due to environmental changes. And the output from the proposed equalizer is finally determined to be 0 or 1.



(a)



(b)



(c)

Figure 4: (a) Histogram of total received image, (b) histogram of zero bit and one bit , (c) accumulative histogram of total received image.

4 BLIND DECISION FEEDBACK EQUALIZER

We have previously proposed a simple and efficient blind equalizer for HVD. However, as shown in Figure 4 (b), there is a little probability of error occurrence when only the blind equalizer using this threshold method is used. Thus, in order to reduce errors due to the data that cannot be distinguished only by the blind equalizer, we propose a blind decision feedback equalizer (blind DFE) by adding a decision feedback loop after the blind equalizer.

The DFE has also been proposed in the field of communications (George et al., 1971). Assuming that previously determined values are correct, the DFE basically attempts to obtain a more accurate output by eliminating the influence of previously determined values on later values, i.e. ISI. Figure 5 shows the structure of the DFE. As shown in the figure, the DFE in the field of communications updates both feedforward filter (FFF), which acts as the equalizer, and feedback filter (FBF) in the feedback loop using the difference between $\tilde{d}[x]$ and $d[x]$.

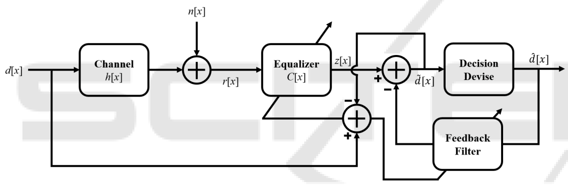


Figure 5: Structure of DFE.

This DFE has the advantage of obtaining accurate output on the assumption that the decisions are correct, but it is difficult to apply to HVD. In the field of communications, DFE effectively eliminates ISI by using 1D FBF for 1D FFF. However, in HVD, when using 2D FBF for 2D equalizer, it is ambiguous to accurately define and use the influence of the previously determined value. Thus, a simple form of DFE without FBF for HDS has been proposed (Marrow and Wolf, 2003). This simple DFE uses decision feedback in the row or column direction instead of using the 2D FBF. It also implies that when the detection process proceeds in the lower right direction, the pixel to be detected is much affected by the upper pixel and the left pixel.

Considering these characteristics, we propose a blind DFE for HVD. Figure 6 represents the structure of the blind DFE. In the feedback loop, z_h^{-1} and z_v^{-1} are unit delay operator in the horizontal and vertical directions, respectively, and K is the scalar multiplying operator.

This blind DFE can be divided into two parts. The front part is the blind equalizer part and the rear part

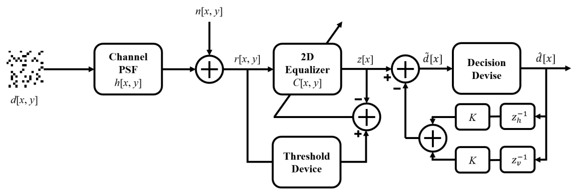


Figure 6: Structure of proposed blind DFE.

is the decision feedback part. As explained in the previous section, in the blind equalizer part, the equalizer is updated by comparing the reference data created by the threshold method with the output of the equalizer, not with the result obtained by subtracting the decision feedback like the DFE in the field of communications. In the decision feedback part, the ISI due to the already determined symbol is removed by feeding back the value obtained by multiplying the determined upper or left pixel values and an appropriate scalar.

In contrast to the conventional DFE, in which the equalizer part and the decision feedback part are coupled together to improve the performance of the equalizer, the blind DFE for HVD is divided into the equalizer part and the decision feedback part, and each part performs their respective roles. In the equalizer part, even if there is some error due to ISI, the data page is roughly restored using the threshold method. In the latter part of the decision feedback, it helps to get more accurate results before the final decision by eliminating the errors due to ISI, that are missed by the blind equalizer.

5 SIMULATION RESULTS

5.1 Simulation Setting

Various BER simulations were conducted to confirm the performance of blind DFE for HVD, because the data rate and robustness increase with increasing BER in the HDS. In all simulations performed in this paper, we simulated 256×256 data pages which have similar size to the European standard. And all data pages are encoded according to European standard codes (ECMA, 2007a; ECMA, 2007b). The HVD channel model is assumed to be a discrete PSF of size 5×5, and thus an equalizer with a 5×5 size coefficient is used. The step size used for updating the equalizer is set to a value of 0.01. The value of scalar K multiplied when the decision feedback was used as 0.1 to reflect the ISI phenomenon of HVD. All BER values resulting from the simulation are the ensemble averages of simulated results of 100 data pages in each environment.

5.2 SNR Simulation

First, we simulated the performance of the blind equalizer for noise. Simulations were performed for various SNRs in an environment with a blur grade of 1.8 and a misalignment of 5 % in the channel model. Figure 7 shows the BER performance to the noise. As can be easily expected, when SNR becomes larger, BER becomes smaller, and the blind DFE has better performance than the blind equalizer. But, the influence of the SNR on the HVD channel model is relatively small, so that the BER variation due to the SNR change is not so severe. In the case of the blind equalizer, when the SNR is 20 or more, the BER is smaller than 10^{-3}, so the data page can be perfectly reconstructed using an error correction code (ECC). On the other hand, when the SNR is less than 20, the BER is larger than 10^{-3}, so there is a possibility that the reconstruction rate will fall. However, in the case of the blind DFE, the BER is much smaller than the blind equalizer. And, as long as the SNR is not too small, the BER is less than 10^{-3}, which makes it possible to restore the data page completely using ECC.

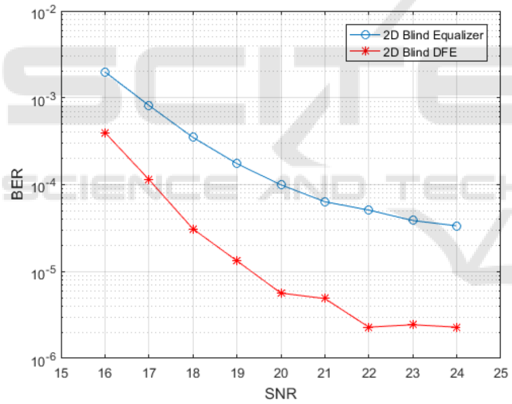


Figure 7: BER performance to the noise.

5.3 Blur Grade Simulation

Secondly, we simulated the performance of a blind equalizer for blur grade. Simulations were performed for varying blur grade in an environment with a SNR of 20 dB and a misalignment of 5 %. Figure 8 represents the BER performance to the blur grade. As can be easily expected, the BER increases as the blur grade increases, and the performance of the blind DFE is better than the blind equalizer. Also, since the blur grade has a large influence on the HVD channel model, it can be seen that the change of blur grade make the BER change a lot. Thus, if the blur grade becomes smaller than 1.7 for the blind equalizer and 1.8 for the blind DFE, the equalizer will restore the data page completely and the number of errors will be zero. Conversely, if the blur grade increases to about 2, the BER may become larger than 10^{-3}, which may result in a decrease in the reconstruction rate of the data page.

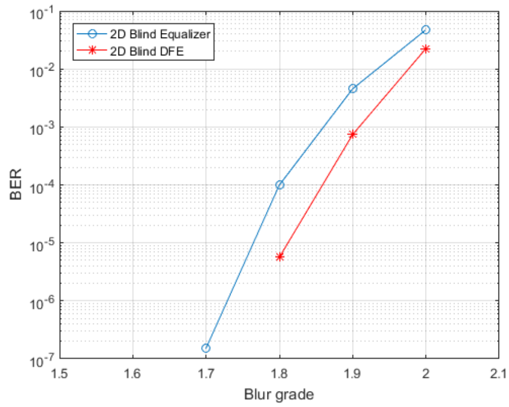


Figure 8: BER performance to the blur grade.

5.4 Misalignment Simulation

Finally, we simulated the performance of a blind equalizer for misalignment. Simulations were performed for various misalignments in an environment with a SNR of 20 dB and a blur grade of 1.8. Figure 9 depicts the BER performance to the misalignment. Also, if the misalignment increases, the BER increases too, and the blind DFE has better performance than the blind equalizer. Similar to the blur grade, larger misalignment can have a catastrophic effect on the performance of the blind equalizer, but there is little chance of misalignment greater than 10 % in the HVD due to sync patterns. Thus, under the assumption that the misalignment is less than 10 %, it is not easy to have a fatal impact on the BER performance.

6 CONCLUSIONS

In this paper, we propose the blind DFE for HVD. The development of the blind DFE has proceeded in two stages.

The first approach was to develop a blind equalizer for HVD. Because HVD data is structurally difficult to match the norm value of a symbol to a specific value, as in the field of communications, it was necessary to design a blind equalizer in a different way from the field of communications. However, since it is necessary to have information that can be referred

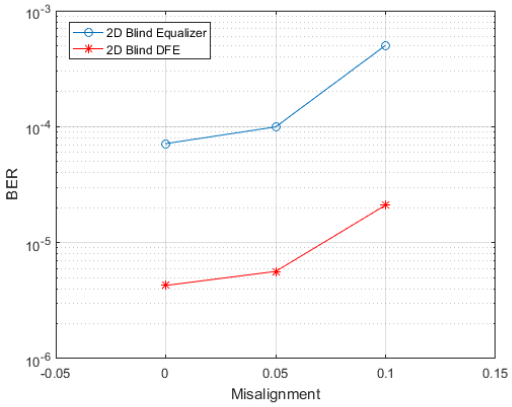


Figure 9: BER performance to the misalignment.

to by the equalizer, a simple threshold method is used to generate information to be referred to by the equalizer, and the equalizer is updated using the information. In addition, the threshold value is determined by analysing the statistical characteristics of the received image, rather than simply using the average value, and thus the same performance can be maintained even when the environment is changed.

The second step is to add a decision feedback loop behind the equalizer in order to compensate for the blind equalizer that may cause errors. In the field of communications, the DFE updated both the equalizer, which act as FFF, and the FBF by comparing the value obtained by subtracting the decision feedback from the equalizer output to the training sequence. However, since it is structurally difficult to implement a 2D FBF in HVD, a decision feedback loop is constructed by multiplying the upper and left pixel values, which have the greatest effect on the current pixel, by an appropriate scalar value.

Although the blind DFE which consists of two parts does not perform the entire equalization process at the same time as the DFE in the field of communications, the data page is roughly restored in the equalizer part even if there is a slight error caused by the ISI, and the effects of errors due to ISI are eliminated in the decision feedback part. As a result, the two parts combine to create the blind DFE for HVD, that effectively removes ISI and performs well.

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