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Performance Comparison of MMSE and Blind Equalization for Digital Holographic Data Storage System

An Sik Choi and Woon Sik Baek*

School of Electronics and Informations, KyungHee University,
Suwon 449-701, KOREA

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In this paper, minimum mean-squared-error(MMSE) and blind equalization schemes were employed to improve bit-error-rate(BER) and to reduce inter-symbol interference(ISI) generated during storage and retrieval processes of two-dimensional data in a digital holographic data storage system. We explained methods for designing and applying MMSE and blind equalization to improve BER in a digital holographic data storage system. From experimental evaluations, we compared the BER performances of MMSE and blind equalization and we showed that the BER performances of MMSE and blind equalization were improved significantly compared with those before equalization.

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I. INTRODUCTION

Information society demands a new data storage system which can store large amounts of data and can read them out fast. An alternative candidate for next-generation data storage system is holographic data storage systems that store data in a 3-dimensional medium such as a photorefractive material [1]. In this new data storage system, data are stored utilizing a holographic scheme, i.e., by superimposing many holograms in the photorefractive medium. Thus, each hologram contains a number of bits equivalent to the number of pixels of the input device such as a spatial light modulator(SLM). In order to launch this holographic data storage system into the market, high reliability of the stored data is required as well as high density and a fast data transfer rate. However, inter-symbol interference(ISI) between adjacent pixels in the process of data storage and retrieval can affect the system performance, i.e., storage capacity and BER [2-5]. Therefore, efforts to improve BER and thus to maximize the storage densities have been made. For this purpose, low-pass codes [2] and equalizations were employed to mitigate ISI [2-5] in a holographic data storage system.

In this paper, minimum mean-squared-error(MMSE) and blind equalization were employed to mitigate ISI and to improve bit-error-rate(BER) for a holographic data storage system.

II. EQUALIZATION METHODS

We employed MMSE and blind equalization methods in a holographic memory system to improve BER and to mitigate ISI generated during the storage and retrieval process of data pages. In the subsequent subsections MMSE and blind equalization schemes are explained. The MMSE and blind equalization methods that are explained in the subsequent subsections do not necessarily model the physics of the holographic data storage system. However, it is important to know the output data for a known input data, so we chose the first data page as reference data to search equalization coefficients.

1. Minimum Mean-Squared-Error Equalization

In order to determine MMSE equalization coefficients that minimize the mean-squared-error $E[|e(k_1,k_2)|^2]$, where error signal $e(k_1,k_2)$ is the difference between the SLM input data $s(k_1,k_2)$ and the previously equalized data $\hat{s}(k_1,k_2)$, we used auto-correlation and cross-correlation of the SLM input data $s(k_1,k_2)$ and CCD output data $x(k_1,k_2)$. The equalized data $\hat{s}(k_1,k_2)$ is given by [6]

$$\hat{s}(k_1,k_2) = x(k_1,k_2) \bigotimes w(k_1,k_2) \tag{1}$$

An equation to obtain MMSE equalization coefficients(= $w(k_1, k_2)$) is given by [4–6]

$$FT[w(k_1, k_2)] = \frac{FT[R_{sx}(k_1, k_2)]}{FT[R_{xx}(k_1, k_2)]} \qquad (2)$$

where FT represents the Fourier transform.

In Eq. (2), $R_{sx}(k_1, k_2)$ is the cross-correlation between the SLM input data and CCD output data, and $R_{xx}(k_1, k_2)$ is the auto-correlation of the CCD output data. To estimate the auto- and cross-correlations, we segmented both the SLM input and CCD output data into 3×3 pixels. Then, we obtained 8×8 pixels by FT estimations of both the auto-correlation and the cross-correlation in Eq. (2). And we selected 3×3 equalization coefficients from the central portion of the 8×8 pixels which was obtained from the inverse FT of the ratio in Eq. (3) [3]. Once the optimum equalization coefficients which have shown the best BER performance are selected by trial and error for the first data page, all CCD output data are convolved with the equalization coefficients of the first data page. Then a threshold value is chosen(by trial and error) for every data page to minimize the BER.

2. Blind Equalization

If the blurring function(point-spread function) $h(k_1, k_2)$ of a holographic channel is not known accurately, $h(k_1, k_2)$ must be estimated. Since we are attempting to deconvolve a blurred image generated by the blurring function of a holographic channel without detailed knowledge of the blurring function, this is called the blind equalization(=deconvolution) [6]. In order to determine blind equalization coefficients, we used SLM input data and CCD output data. The equations to obtain blind equalization coefficients are

$$\begin{aligned} x_{ij}(k_1, k_2) &= s_{ij}(k_1, k_2) \otimes h_{ij}(k_1, k_2) \\ X_{ij}(w_1, w_2) &= S_{ij}(w_1, w_2) \cdot H_{ij}(w_1, w_2) \\ H_{ij}^{-1}(w_1, w_2) &= \frac{S_{ij}(w_1, w_2)}{X_{ij}(w_1, w_2)} \end{aligned} \qquad (3)$$

In Eq. (3), $s_{ij}(k_1, k_2)$ and $x_{ij}(k_1, k_2)$ are the subimages of the SLM input and CCD output data, respectively. To estimate the equalization coefficients, we segmented both the SLM input and CCD output data into 3×3 pixels. Then, we obtained 8×8 pixels by FT estimations of both the SLM input and CCD output data, and we selected 3×3 equalization coefficients from the central portion of the 8×8 pixels which was obtained from the inverse FT of the ratio $\{S_{ij}(w_1, w_2)/X_{ij}(w_1, w_2)\}$. Once the optimum blind equalization coefficients which have shown the best BER performance by trial and error are selected for the first data page, all CCD output data are convolved with the equalization coefficients of the first data page. Then a threshold value is chosen(by trial and error) for every data page to minimize the BER.

III. EXPERIMENTAL RESULTS OF THE MMSE AND BLIND EQUALIZATION

We used 50 data pages provided by Daewoo Holographic Data Storage Group and each page contain 192×192 pixels. A schematic diagram of experimental setup is shown in Fig. 1. A diode-pumped Nd-YAG laser with a maximum output power of 200 mW at 532 nm was used as a light source. The light beam from the laser was expanded by a high-power beam expander and split by a polarizing beam splitter(PBS) into the signal arm and the reference arm. The polarization of the beam was changed in a half-wave(HW) plate. The signal beam was filtered by a spatial filter and modulated by a CRL XGA1L12 SLM with 1024×768 pixels and 100:1 contrast ratio. The modulated signal beam was Fourier-transformed by a lens with a 125 mm focal length and was filtered by optical aperture(OA) which was opened by Nyquist width. For detection, a Photometrics Sensys CCD camera with a 1536×1024 Kodak KAF1620E CCD chip was adopted and it was operated in the 4×4 binning mode with a pixel matching configuration. The reference beam was encoded in the random phase by a Newport holographic diffuser which enables speckle shift multiplexing. The reference beam interfered with the signal beam in a Fe-doped LiNbO$_3$ crystal with a 45 cut and the recording time was fixed for all data pages. In order to prevent the saturation of the recording media, we defocused the beam 1cm behind the focal plane of the lens. Holograms were recorded by speckle shift

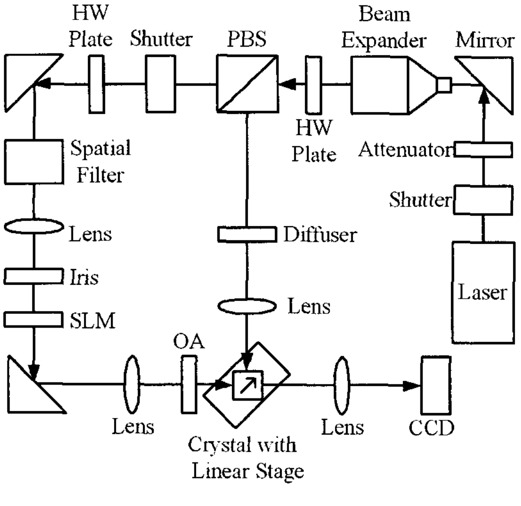


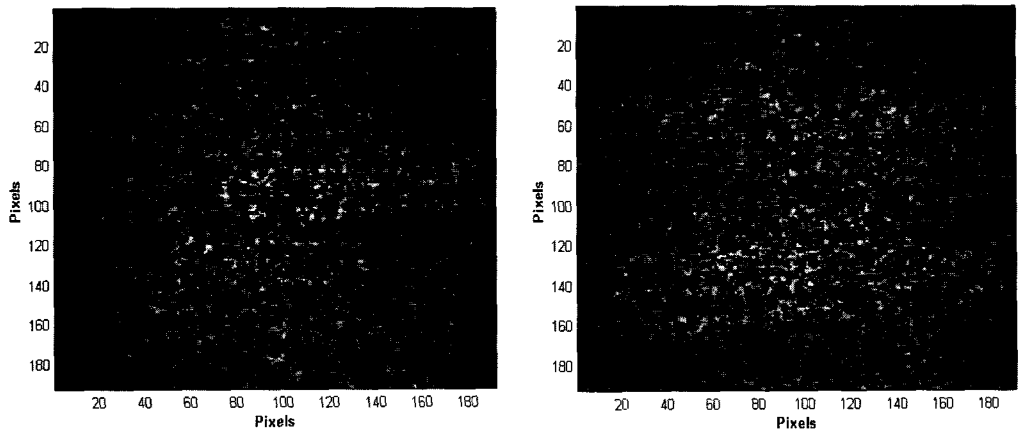
FIG. 1. Experimental setup.

TABLE 1. Normalized MMSE equalization coefficients for page 1.

	x_{-1}	x_0	x_1
y_{-1}	0.0180	-0.0921	-0.0304
y_0	-0.0508	1.0	-0.0169
y_1	-0.0936	-0.0957	-0.0068

TABLE 2. Normalized blind equalization coefficients for page 1.

	x_{-1}	x_0	x_1
y_{-1}	-0.0092	-0.0795	-0.0013
y_0	-0.0748	1.0	-0.0748
y_1	-0.0013	-0.0795	-0.0092



(a) (b)

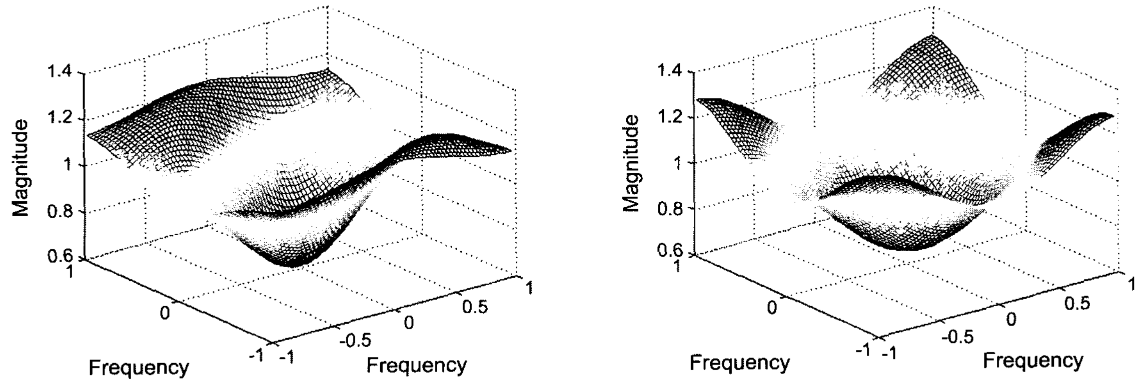
FIG. 2. The retrieved data pages from holographic data storage. (a) page #1. (b) page #50.

multiplexing with a 20 μm separation. A Physik Instrument(PI)M-510 motorized linear stage(0.5 μm resolution) was used for this purpose. Fig. 2 shows retrieved data pages from holographic data storage.

We determined MMSE and blind equalization coefficients by the method explained in the section II. Tables 1 and 2 show the normalized MMSE and blind equalization coefficients, respectively. We investigated the frequency responses of the equalizers and Fig. 3 shows the frequency responses of the equalizers with coefficients shown in Tables 1 and 2. Fig. 4 is a histogram which shows the equalization effects for data page 1. From Fig. 4, we can say that equalization mitigates ISI between pixels. Therefore, we can separate the 1's and 0's more distinctively.

We estimated the BER and signal-to-noise ratio (SNR) performances of MMSE and blind equalization. The SNR [7] which is defined as assessing the relative quality of image is

$$SNR = \frac{\mu_1 - \mu_0}{\sqrt{\sigma_1^2 + \sigma_0^2}} \tag{4}$$



(a) (b)

FIG. 3. Frequency responses of equalizers. (a) MMSE equalization. (b) blind equalization.

TABLE 3. Number of errors for 50 data pages.

Method	Number of errors
Without equalization	6032
With MMSE equalization	1644
With blind equalization	1131

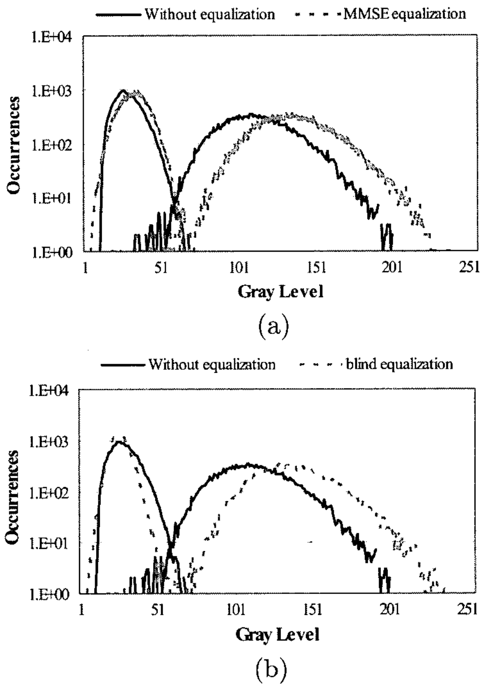


FIG. 4. Histogram showing equalization effect. (a) MMSE equalization. (b) blind equalization.

where μ_1 and μ_0 are the means, and σ_1^2 and σ_0^2 are the variances of on and off pixels, respectively.

The experimental results of the BER and SNR are shown in Figs. 5 and 6. And Table 3 shows the number of errors without and with equalization for 50 data pages. It turned out that the BER performances for 50 data pages were improved by approximately 73%(for MMSE equalization) and 81%(for blind equalization). The average BER for 50 data pages was estimated by approximately 3.3×10^{-3}(without equalization), 8.9×10^{-4}(with MMSE equalization), and 6.1×10^{-4} (with blind equalization), respectively. The reason blind equalization gave better results than MMSE equalization is that the frequency response of the blind equalizer has better high-pass characteristics than that of the MMSE equalizer as is shown in Fig. 3. The SNR also improved after equalization. From experimental results, it is clear that MMSE and blind equalization can improve the BER and SNR. Also the storage capacity improvement can be achieved by the use of the MMSE and blind equalization.

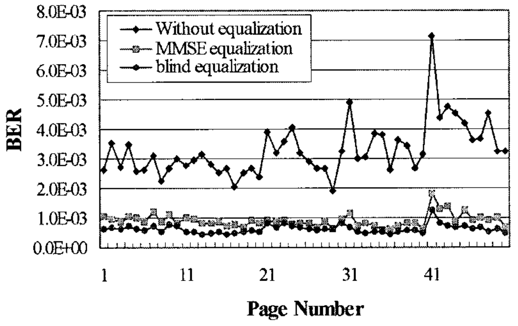


FIG. 5. BER performances of data pages before and after equalization.

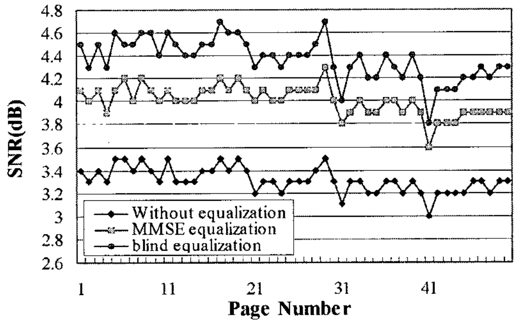


FIG. 6. SNR performances of data pages before and after equalization.

IV. CONCLUSION

In this paper, we employed the MMSE and blind equalization methods to mitigate ISI generated during storage and retrieval processes of data pages in a holographic data storage system. We described the methods for designing and applying MMSE and blind equalization to improve BER in a holographic data storage system. From experimental results using 50 data pages, we showed with fair certainly that the BER and SNR performances of MMSE and blind equalization were improved compared with those before equalization.

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*Corresponding author : wsbaek@khu.ac.kr.

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