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Communication

A Two Dimensional Partial-Response Maximum-Likelihood Technique for Holographic Data Storage Systems

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In holographic data storage systems, it is straightforward to increase the storage capacity by mean of reducing the pitches among data symbols. However, this may lead to severe inter-symbol interference (ISI) and also unacceptable data error rate. To deal with the problem, we first model the channel as a partial response (PR) and use the maximum-likelihood (ML) detection to control the ISI. The Viterbi decoder is employed to implement ML detection. [DOI: 10.1143/JJAP.47.5997]

KEYWORDS: optical storage, holographic recording, PRML, partial response and maximum likelihood

Holographic data storage (HDS) system is currently regarded as the optical storage systems of next generation, because of its high data transfer rate and high capacity.[1,2] To increase the capacity, higher density of recorded data is required. Besides, when the number of pages multiplexed in the same volume increases, a small optical aperture is necessary. This may result in pixel blurring due to diffraction. Thus, the problem of inter-symbol interference (ISI) becomes severe. To overcome ISI, some methods are proposed. Kumar[3] used digital equalization and low-pass encoding to deal with ISI. Hesselink[4] proposed several detection methods, such as threshold detection and Viterbi detection, to relieve the effects of ISI. Though partial response (PR) equalization with ML detection has been widely used in many data storage systems, little is developed for HDS systems. In this paper, we would like to propose a two-dimension partial response and maximum-likelihood (2D-PRML) technique for a class of HDS channel to control the ISI and then apply to two PR models as examples.

A typical channel of the HDS system is shown in Fig. 1, where f is an N-by-M array to represent the spatial light modulator (SLM) image, g is the charge-coupled device (CCD) output image of the same dimension as f, w is the point spread function (PSF), and n denotes the noise disturbance. The CCD pixel output $g[m,n]$ is given by

$$g[m,n] = w \otimes f + n[m,n]. \tag{1}$$

Here we assume that the PSF w can be decomposed as $w = w_{\mathrm{v}} w_{\mathrm{h}}^{\mathrm{T}}$ with vectors w_{v} of dimension P and w_{h} of dimension Q. Vectors w_{v} and w_{h} can be regarded as the channel responses along column direction (vertical) and row direction (horizontal), respectively. With the assumption, eq. (1) can be further derived as

$$\begin{aligned} g[m,n] &= \sum_{p=-\bar{P}}^{\bar{P}} \sum_{q=-\bar{Q}}^{\bar{Q}} w[p,q] f[m+p, n+q] + n[m,n] \\ &= \sum_{p=-\bar{P}}^{\bar{P}} \sum_{q=-\bar{Q}}^{\bar{Q}} w_{\mathrm{v}}[p] w_{\mathrm{h}}[q] f[m+p, n+q] + n[m,n] \\ &= \sum_{p=-\bar{P}}^{\bar{P}} w_{\mathrm{v}}[p] \sum_{q=-\bar{Q}}^{\bar{Q}} w_{\mathrm{h}}[q] f[m+p, n+q] + n[m,n], \end{aligned} \tag{2}$$

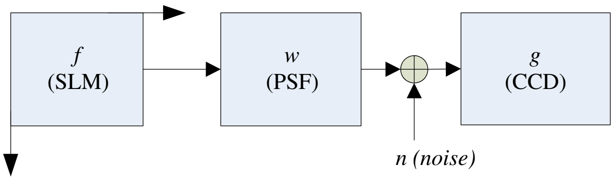

Fig. 1. (Color online) Block diagram of HDS channel.

where $\bar{P} = (P-1)/2$ and $\bar{Q} = (Q-1)/2$. If we define

$$g_p[m+p, n] = \sum_{q=-\bar{Q}}^{\bar{Q}} w_{\mathrm{h}}[q] f[m+p, n+q]. \tag{3}$$

Then eq. (2) becomes

$$g[m,n] = \sum_{p=-\bar{P}}^{\bar{P}} w_{\mathrm{v}}[p] g_p[m+p, n] + n[m,n]. \tag{4}$$

The pixel output is calculated in two stages. First, in eq. (3), we convolve f with w_{h} to obtain response $g_p[m+p,n]$ contributed by the $(m+p)$th row of f. Then, eq. (4) computes the convolution of g_p and w_{v} along the column direction for the pixel output. The HDS channel represented by eqs. (3) and (4) is plotted in Fig. 2. Decoupling of matrix w brings us an advantage to transform the 2D data detection problem into a one-dimensional (1D) case. In the following, we give two models as examples, and these models are also employed to be the PR models in numerical simulations. Then the Trellis diagrams according to the models are derived for implementing the maximum-likelihood (ML) detection.

$$\text{PR Model 1: } w = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

It is straightforward to know that $w_{\mathrm{v}} = [1\ 1]^{\mathrm{T}}$ and $w_{\mathrm{h}} = [1\ 1]^{\mathrm{T}}$ decompose w. Suppose that the data bits in f are binary (0 or 1), and then the output levels of w_{h}, i.e., the levels of g_p, can be calculated as 0, 1, and 2 according to eq. (3). Since g_p is just the input of block w_{v}, we can compute the CCD pixel output g to be either 0, 1, 2, 3, or 4 with eq. (4). If we define Si as the Trellis state for i to be the previous input, the Trellis diagram of w_{h} can be plotted as Fig. 3(a). In the figure, a/b denotes the information of the state transition with $a \in \{0,1\}$, the current input and $b \in \{0,1,2\}$, the output level. Likewise, block w_{v} with input

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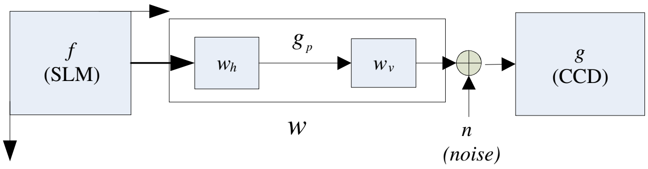

Fig. 2. (Color online) Decoupled diagram of HDS channel.

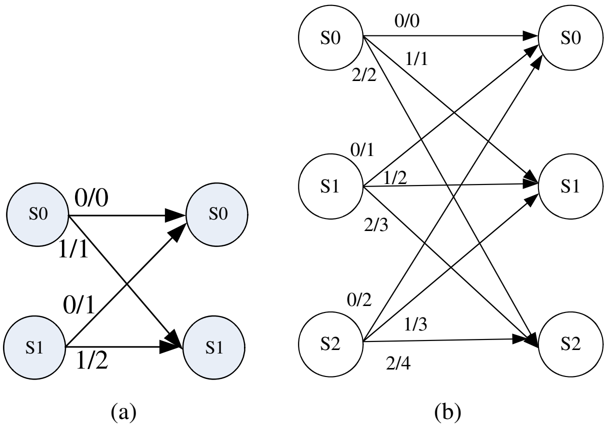

Fig. 3. (Color online) Trellis diagrams of PR1: (a) w_v; (b) w_h.

$g_p \in \{0, 1, 2\}$ and output $g \in \{0, 1, 2, 3, 4\}$ can be also represented as the Trellis diagram in Fig. 3(b).

$$\text{PR Model 2: } w = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

In this case, we have $w_v = w_h = [1\ 2\ 1]^T$. Now, let the Trellis state be Sij for i the previous input and j the input before i. Along the same way as in the last case, the Trellis diagrams can be shown as Figs. 4(a) and 4(b). In Fig. 4(b), the total number of states is 25 and the pixel output levels are $0, 1, \ldots, 16$. Such Trellis diagram may not be a good candidate for the design of ML Detector due to its complexity. To deal with this problem, we utilize the modulation code (1/3 code) proposed by Tarng *et al.*[5] Since the input sequence to the PR model is modulated by the encoder, the number of states and the transitions among them can be effectively reduced. This can be observed from the Trellis diagrams in Figs. 5(a) and 5(b).

In the case studies above, we decomposed the PR models into row response w_h and column response w_v. The new representation transforms the channel into two 1D sub-channels connected in series. Since we have derived the Trellis diagrams, the ML detection can now be achieved by using Viterbi algorithm. First, we apply the algorithm with the Trellis diagrams of w_h to the detection of the corrupted data along row direction, and we call this process as row detector. The row detector can eliminate the ISI among pixels in the same row. The output of the row detector is then fed to the so-called column detector, which is used to tackle the ISI along column detection. The column detector is implemented with the Trellis diagram of w_v, and the Viterbi algorithm is still employed for ML detection. Since the 2D ISI is coped with for both directions, the data can be recovered successfully.

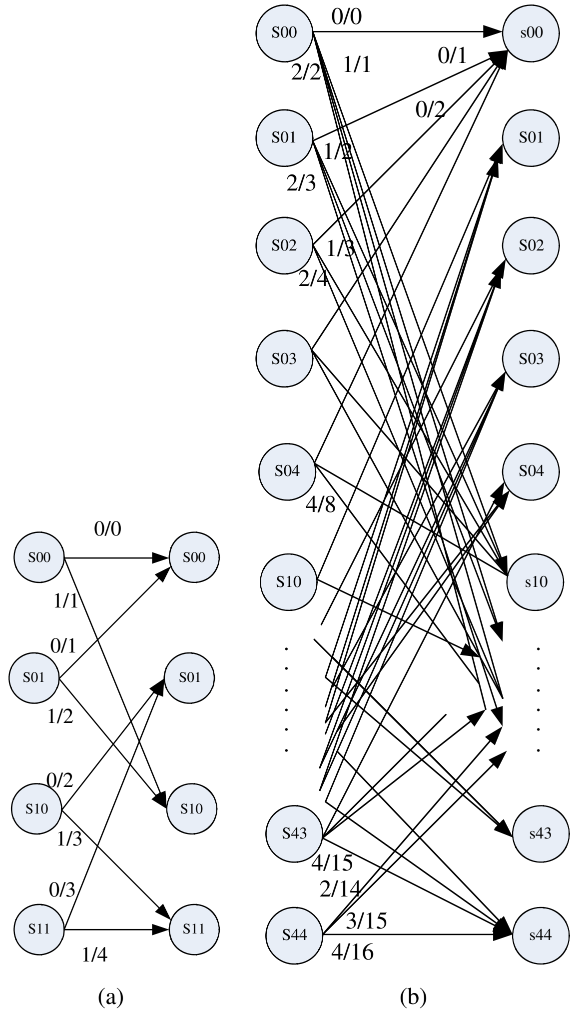

Fig. 4. (Color online) Trellis diagrams of PR2: (a) w_v; (b) w_h.

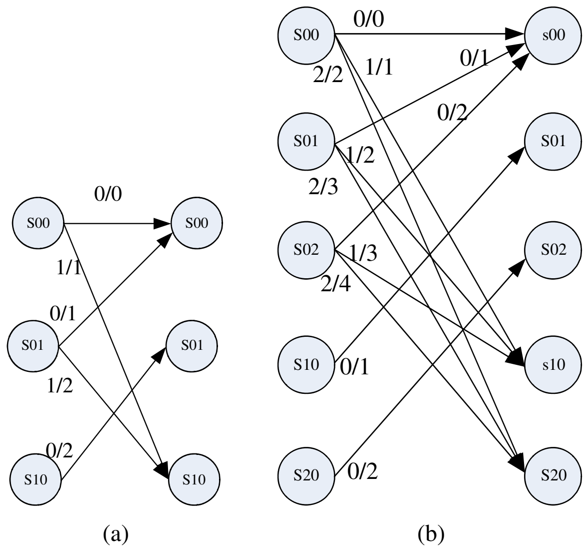

Fig. 5. (Color online) Trellis diagrams of PR2 with 1/3 modulation code: (a) w_v; (b) w_h.

To verify the effectiveness of the proposed method, we perform computer simulations by using additive white Gaussian noise (AWGN) channel model. The results are compared with those of conventional equalization detectors — minimum mean square error (MMSE) equal-

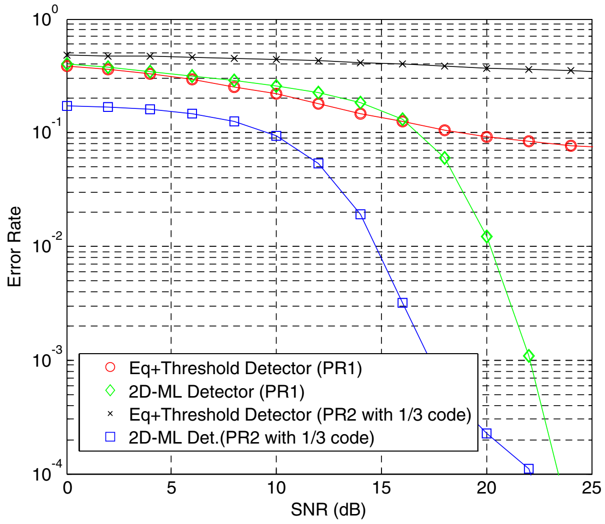

Fig. 6. (Color online) Performance comparison.

ization + threshold detector. The simulation results are depicted in Fig. 6. Figure 6 shows the error rate versus signal-to-noise ratio (SNR) with two methods in different PR models. In our two simulated PR channels (PR1 = $[1\ 1]^T \times [1\ 1]$ and PR2 = $[1\ 2\ 1]^T \times [1\ 2\ 1]$), the ISIs are all serious and the equalization detector is incapable of giving satisfactory result. When the 2D-ML detector is applied, it is obvious that the performance is significantly improved. Moreover, Fig. 6 shows that the 2D-ML method used in PR2 with $1/3$ modulation code has the best performance among all cases.

The computation complexity of 2D-ML detection makes it inapplicable in HDS systems. To deal with such problems, this paper proposed a 2D-PRML scheme. We presented two kinds of 2D partial response models and ML detectors to control ISI completely. The simulation results also show that the 2D-PRML technique cooperated with modulation codes can offer benefits in reducing the complexity of the detector design and improving the performance of data detection.

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