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Iterative Decoding between Two-Dimensional Soft Output Viterbi Algorithm and Error Correcting Modulation Code for Holographic Data Storage

Jinyoung Kim, Yong Moon*, and Jaejin Lee

School of Electronic Engineering, Soongsil University, Seoul 156-743, Korea

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We propose an iterative decoding scheme for holographic data storage that uses modulation codes with a trellis structure to obtain some coding gain. Furthermore, the iterative scheme between a channel detector and the modulation code can achieve more coding gain. In the simulation, when there are (10%, 10%) and (20%, 20%) misalignments, the proposed iterative scheme with a pseudorandom interleaver performs approximately 0.3 and 1 dB better, respectively, compared to the scheme without iteration.

1. Introduction

A holographic data storage channel requires modulation codes to mitigate two-dimensional intersymbol interference (2D ISI) to maintain the ratio of ON and OFF pixels, thereby reducing interpage interference (IPI).[1,2] In order to reduce 2D ISI, researches have been conducted to eliminate fatal isolated patterns (i.e., where the pattern is surrounded by different pixels).[3–7] However, they do not have extra coding gain, unlike modulation codes with a trellis structure.[8–10] In particular, Kim *et al.* introduced an error correcting the modulation code for holographic data storage.[10] Here, we can generate an iterative scheme between the channel detector and the modulation code.

Iterative decoding (or detection) schemes have improved the performance of many communication systems. The turbo equalizer that performs iterative decoding between channel detector and error correcting code, in general, achieves good performance. Since the error correcting modulation code[10] can be considered an error correcting code, it is possible to perform iterative decoding between the detector and modulation code. In this paper, we propose an iterative decoding method for holographic data storage between the 2D soft output Viterbi algorithm (SOVA), a channel detector, and the error correcting modulation code.

2. Iterative Decoding between 2D SOVA and Error-Correcting Modulation Code

The error-correcting modulation code is able to correct errors because it has parity symbols. For iterative decoding between 2D SOVA and the error-correcting modulation code, the input and output format of both 2D SOVA and the modulation code decoder must have the same soft-in soft-out (SISO) data type. Unfortunately, however, 2D SOVA decodes SISO data per bit,[11] while the error-correcting modulation code decodes SISO data per M-ary symbol.[12] The modulation code we are considering[10] is the mapping between four user (or message) bits and six codeword bits. Thus, the modulation code decoder outputs a codeword symbol corresponding to a block of four bits, and there are 16 codewords. Therefore, for the error correcting modulation code, nonbinary SOVA generates a vector of log-likelihood ratio (LLR) with 16 elements. We define each element of the vector LLR as follows:

$$L_{k,\mu} = \log\left[\frac{\Pr(u_k = \mu|\mathbf{r})}{\Pr(u_k = 0|\mathbf{r})}\right],$$

where $L_{k,\mu}$ is the LLR of $\mu \in \{0, \dots, 15\}$ for kth symbol u_k, and $\mathbf{r}$ is the received signal. This vector LLR should be converted into the corresponding six bit LLRs in order to send the extrinsic information from the 2D SOVA to the modulation code decoder. The bit level LLR $\Lambda_{k,j}$ for jth bit of kth symbol is defined by

$$\Lambda_{k,j} = \mathrm{sgn}(\mu_j^{\max}) \times \left|\log\left[\frac{\sum_{\substack{\mu=0\\ \mu_j=1}}^{15} \exp(L_{k,\mu})}{\sum_{\substack{\mu=0\\ \mu_j=0}}^{15} \exp(L_{k,\mu})}\right]\right|$$

where μ_j is the jth bit of the codeword μ, and $\mu_j^{\max}$ is μ_j such that $\max_\mu\{L_{k,\mu}\}$. This value is the extrinsic information $m[p,q]$, and error correcting modulation code outputs $m[p,q]$ to the 2D SOVA.

The 2D SOVA is composed of two 1D SOVAs, one for the horizontal and one for the vertical direction.[11] Each 1D SOVA receives the output of an equalizer depending on the partial response (PR) target of the corresponding direction. The 2D SOVA generates an average of two 1D SOVA outputs. Thus, we use the 2D SOVA as a channel detector for the turbo equalizer. Generally, a serial turbo equalizer requires an interleaver. In this paper, we exploit a pseudorandom interleaver expressed in terms of the codeword symbol.

Figure 1 shows the turbo equalizer with the error correcting modulation code for the proposed iterative system. Here, α is an attenuator that controls the amount of extrinsic information from the modulation code decoder. If this value is too large, the priori information received from the interleaver can affect the performance of 2D SOVA too much. Conversely, if this value is too small, so too will be the effect of the priori information, and therefore the iterations will not help to improve the performance. Therefore, α must be selected to have an appropriate value so that the priori information will have little effect on the 2D SOVA; it will then show better performance in the iterations. In this paper, we use a value of 10 for α.

3. Simulation Results

3.1 Conditions of the simulation

A block diagram of the whole system is given in Fig. 2. Here, $a[k]$ represents binary sequential input data, and the modulation code encoder converts $a[k]$ to 2D data $d[p,q]$; $d[p,q]$ is changed to $\tilde{d}[p,q]$ by the interleaver, and then $\tilde{d}[p,q]$ passes through the holographic channel. The 2D holographic channel is implemented by.[1] The data that have

*E-mail address: moony@ssu.ac.kr

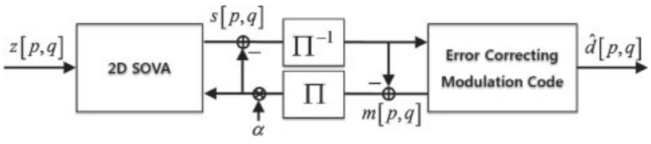

Fig. 1. Turbo equalizer with 2D SOVA and error-correcting modulation code.

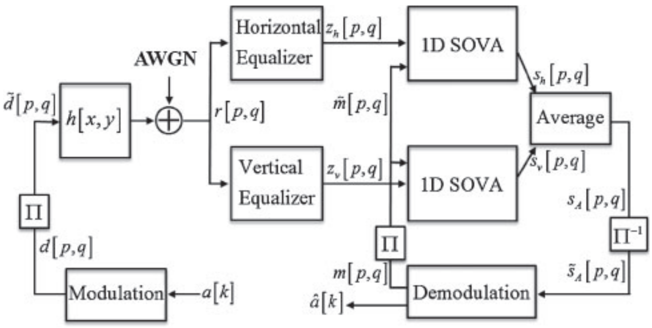

Fig. 2. Block diagram of the whole system.

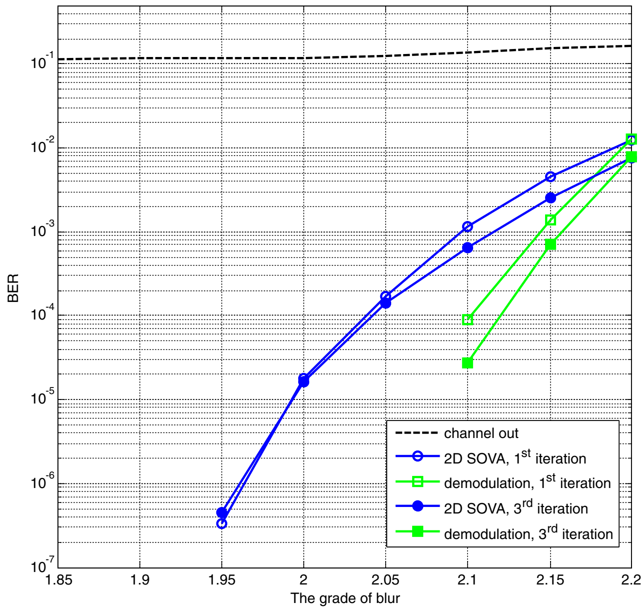

Fig. 3. (Color online) BER performance in accordance with the blur.

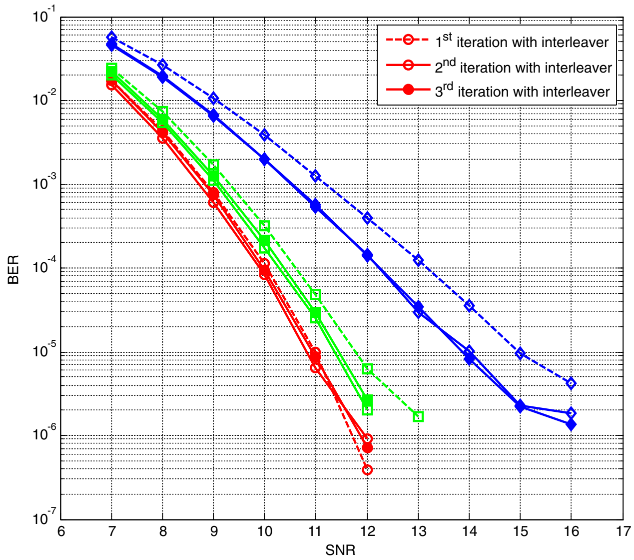

Fig. 4. (Color online) BER performance with an interleaver. The curves of the circle, square, and diamond markers represent the performance of no misalignment, (10%, 10%) misalignment, and (20%, 20%) misalignment, respectively.

passed through the channel are added to additive white Gaussian noise (AWGN), which is represented by $r[p,q]$. Then, $r[p,q]$ goes to the horizontal and vertical equalizers, which are trained by each PR target. After passing through the equalizers, $z_h[p,q]$ and $z_v[p,q]$ enter each 1D SOVA, respectively, as an input. After averaging the two 1D SOVA outputs, the average value passes through the interleaver and demodulation. The output of the demodulation is a symbol LLR that is converted to a bit LLR. The bit LLR is input into the 1D SOVAs as the priori information, and then the iterative decoding progresses.

In order to evaluate several channel sequences for holographic data storage, we simulated 1,000 pages with a size of 1024×1024 pixels per page. The grade of blur of the holographic channel is 1.85. The PR targets of both the x- and y-directions are the same as for PR(131). We define the channel signal-to-noise ratio (SNR) as $10\log_{10}(1/\sigma^2)$. The error-correcting modulation code has one parity symbol per 30 codeword symbols.

3.2 Simulation result

While the grade of blur is varying from 1.85 to 2.1, a bit error rate (BER) performance without AWGN is shown in Fig. 3. For the first iteration, the channel detection and demodulation of the error-correcting 4/6 modulation are performed only once, such as if there were no iteration. The BER of channel output data is derived by comparing $\tilde{d}[p,q]$ with $r[p,q]$ using threshold detection scheme, in other words the simple level detection. This result shows that the BER is greater than 10^{-1} if the detection and demodulation scheme are not applied. Also, while the 2D SOVA's BER performances of both first and third iterations are similar, the demodulation's BER performance of third iteration is better than that of first iteration.

Figure 4 shows the BER performance with the interleaver. The curves of the first, second, and third iteration are represented by dashes with hollow markers, solid lines with hollow markers, and solid lines with solid markers, respectively. In addition, the curves of the circle, square, and diamond markers represent the performance of no misalignment, (10%, 10%) misalignment, and (20%, 20%) misalignment, respectively. The misalignment amounts denote (x-axis, y-axis) misalignments. When there is no misalignment, there is not much performance gain for the iterative decoding. When there are (10%, 10%) and (20%, 20%) misalignments, there are approximately 0.3 and 1 dB gains, respectively. However, even if the number of iterations is increased, the performance gain is limited. As

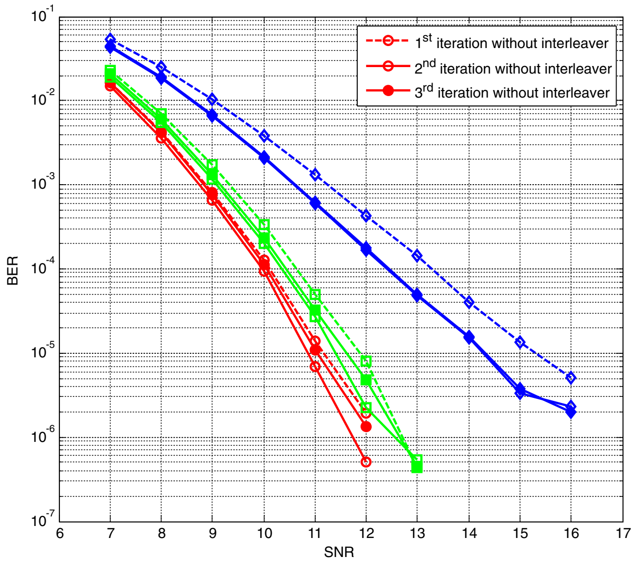

Fig. 5. (Color online) BER performance without an interleaver. The curves of the circle, square, and diamond markers represent the performance of no misalignment, (10%, 10%) misalignment, and (20%, 20%) misalignment, respectively.

shown in the simulation result, the iterative scheme exhibits good performance for misalignment noise. The BER performance in the absence of the interleaver is shown in Fig. 5. Here, the change of the performance shows a similar trend to that in Fig. 4, but the overall performance with the interleaver is shown to be better than that without the interleaver. The inclusion of the interleaver results in some performance gains. We expect that the iterative decoding between 2D SOVA and the error-correcting modulation code will demonstrate its true worth when collaborating with some outer code, such as a turbo code.

4. Conclusions

We proposed an iterative decoding between 2D SOVA and an error-correcting modulation code for holographic data storage. In addition, we proposed a method of changing the vector LLR to bit LLRs in order to use the iterative scheme. We compared the BER performance of the iterative scheme with and without an interleaver. The iterative scheme has increased complexity, but exhibits good performance in terms of misalignment noise. The iterative scheme shows a performance that is approximately 0.3 and 1 dB better than no iterative scheme at (10%, 10%) and (20%, 20%) misalignment, respectively. This will exhibit its true worth when collaborating with some outer code, such as a turbo code.

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