Holographic storage scheme based on digital signal processing

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In this paper, a holographic storage scheme for multimedia data storage and retrieval based on the digital signal processing (DSP) is designed. A communication model for holographic storage system is obtained on the analogy of traditional communication system. Many characteristics of holographic storage are embodied in the communication model. Then some new methods of DSP including two-dimensional (2-D) shifting interleaving, encoding and decoding of modulation-array (MA) code and method of soft-decision, etc. are proposed and employed in the system. From the results of experiments it can be seen that those measures can effectively reduce the influence of noise. A segment of multimedia data, including video and audio data, is retrieved successfully after holographic storage by using those techniques.
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Holographic data storage has potential for high data density and high data transfer rate. These characteristics make it the focus of the storage development and some noticeable effects have been made recently. But there are various noise sources in the system, which block it to be utilized[1,2].

By using proper hardware and some kinds of digital signal processing (DSP) in holographic storage experiments, remarkable effects have been made in this field. But till now multimedia data storage and retrieval have not been reported in China. To make full use of the potentials of the holographic storage system, some DSP methods must be used. But they are not suitable for a certain condition sometimes. For example, the error-correction coding (ECC) in Ref. [3] is valid for reducing noise, but the code rate is low. When it combines with the constant weight code, the shortcoming can be overcome. This suggests that the combination of modulation code and ECC may yield more effective code structures, and the iterative decoding techniques[4−6] can be reformed. A 2-D cyclic shifting interleaving[7,8] can be also used before encoding.

Methods used in the scheme are all appropriate. Some of them are concluded from many references, e.g. the communication model which cannot be found directly in those papers. The other of them are designed for the experimental condition, e.g. the 2-D cyclic shifting interleaving which is different from other interleaving in references. Especially we invent the modulation-array (MA) code which is the combination of modulation and ECC. Accordingly the soft-decision is designed. From the results of experiments, it can be seen that those measures can effectively reduce the influence of noise.

In order to make a hologram, two coherent beams called the reference and object beams are overlapped in a photosensitive medium. The interference pattern generates chemical and/or physical changes in the storage medium. When the readout beam illuminates the raster in the medium, some of the light is diffracted to "reconstruct" a weak copy of the object beam[1,2]. Comparing this process with the communication system, it can be found that the two processes resemble in many aspects. Then the holographic system can be considered as a non-real-time communication system. The interference of reference and object beam has the same function of the modulation of carrier wave by the signal. Storage medium may be regarded as the channel for communication. Accordingly the demodulation of holographic system is the process of the hologram read out by illuminating with the reading beam. According to the above description, the communication model of digital holographic storage system (DHSS) is schematically shown in Fig. 1.

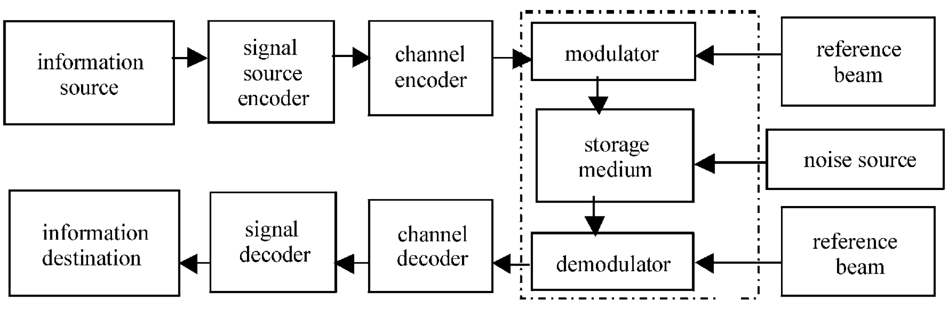

Fig. 1. The communication model of digital holographic storage system.

In this model, the processing of hologram recording and read-out occurs in the storage medium. Since in this paper we want to study the electrical signals, the optical path from the spatial-light modulator (SLM) to the charge-coupled device (CCD) is considered as one part, i.e. the storage channel.

Each of other parts in the storage system corresponds to one part of the model in Fig. 1. We will describe them one by one as follow.

1) Information source: the data to be stored.

2) Signal source encoder: the encoder has two major functions.

Data compression is not necessary in the scheme. So the encoder in the system only converts the format of data. The data after conversion are binary images which can be displayed on SLM and can be easily stored. The dark dot of binary image represents 0 of the original data. Whereas the bright dot represents 1. The process is shown in Fig. 2.

In the experiment if the image reconstructed on CCD does not cover the whole area of CCD, an additional frame is necessary to the original data image. It acts as the synchronous bits. The framed image finally stored in the medium is shown in Fig. 3.

3) Channel encoder. This part is very important in our scheme. It can be divided into three sub-parts according to their functions: error-correction encoder, interleaver and modulation encoder.

Error-correction encoder. The error-correction in the field of communication is well developed, so we can select the proper error-correction code that is suitable for DHSS based on a detailed analysis of the storage channel. Currently the Reed-Solomon code is adopted popularly in DHSS[9]. So 16×18 array code is chosen in our scheme.

Interleaver. The function of this part is to change the order of the data. The correlation of the data becomes very little after interleaving. Then the influence of Burst error also decreases. The holographic channel is a 2-D channel, so the multidimensional interleaving is needed. To match the 8×10 MA code of the scheme, a 2-D cyclic shifting interleaving[7,8] is designed. The steps are shown as:

(1) The horizontal interleaving degree is 8.

(2) The vertical interleaving degree is 8.

(3) The horizontal cyclic shifting degree of the nth row is n.

(4) Lastly, the vertical cyclic shifting degree of the nth column is $2n$.

Modulation encoder. The constant weight code is a very popular modulation code currently. But it has no the function of error-correction. Then the MA code was designed as the modulation code. It takes advantage of the constant weight code, ECC and iterative decoding. The new soft-decision according to the new code is designed too. So noise can be removed effectively in this way. The MA code will be described in what follows.

4) Channel decoder. It has the opposite function of channel encoder. In a word, it retrieves the data before channel encoding. Output of CCD includes a great deal of noise. So the proper filter is necessary before Channel decoding.

The noise in holographic storage is very complex. If Wiener filter or Kalman filter is used directly, the noise cannot be removed effectively. And the reference signal of adaptive filter is difficult to get. We find out that the inter-symbol interference (ISI) is very severe in experiment. So regional 2-D equalization is adopted to restrain the noise firstly in the storage scheme[3,10].

The relation between input and output of $(2N-1) \times (2N-1)$ minimum mean square error 2-D equalizer is shown as

$$R_{di}(m,n) = \sum_{j=-N+1}^{N-1} \sum_{k=-N+1}^{N-1} w(j,k) * R_{ii}(m-j, n-k)$$
$$= w(m,n) \otimes R_{ii}(m,n),$$

where $R_{di}(m,n)$ is the 2-D correlation between the input and the anticipant output. $R_{ii}(m,n)$ is the 2-D auto-correlation of input. $W(m,n)$ is the coefficient of equalizer.

The signal after filtering is demodulated, de-interleaving and error-correction decoded. The decoding is the opposite process of encoding. Reference [11] describes how to decode the MA code. Similarly de-interleaving is the opposite process of interleaving.

5) signal source decoder. It removes the additional frame added when encoding.

6) information destination. The data is retrieved lastly.

Then the original format of data can be retrieved. The process is shown in Fig. 4.

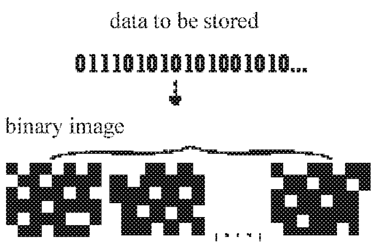

Fig. 2. Conversion diagram of writing data.

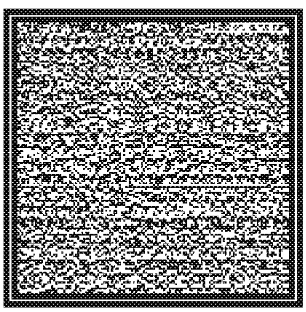

Fig. 3. A storage image.

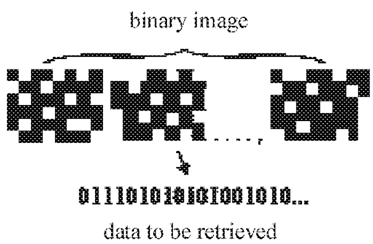

Fig. 4. Conversion diagram of reading data.

The conventional quantizer has only one function, which is to transform the pseudo-analog signal received by CCD into binary data, because it is behind the filter directly. So lots of information in the pseudo-analog signal is lost during this data processing and the quantity of losing information will increase rapidly as the signal-to-noise ratio (SNR) of the pseudo-analog signal goes down. Another result is that the quantity of information inputting into error-correction decoder speedily lessens as the number of stored pages increases. All these make the user bit error rate (BER) climb up acutely and higher storage density cannot be achieved.

In order to overcome the disadvantages described above we need extend the function of quantizer. The design is realized by modifying the inherent structure of traditional modulation codes [12,13] by incorporating ECC in it, and let ECC sufficiently use information in the pseudo-analog signal[4]. The MA code we proposed here is one modified modulation code by incorporating array code with ECC in it. The code structure is shown in Fig. 5.

Region of modulation code is in left, which includes $k \times k$ symbols. From left to right: $\{x(1,1),\ x(1,2),\ \cdots,\ x(1,k)\},\ \cdots,\ \{x(k,1),\ x(k,2),\ \cdots,\ x(k,k)\}$ are k codewords of $n:k$ modulation code in order. Region of checkout is in right, which includes $k \times 2$ symbols. The relation between $h(1), h(2), \cdots, h(k-1), h(k)$ and symbols in left is

$$h(i) = x(1,i) \oplus x(2,i), \cdots, \oplus x(k-1,i) \oplus x(k,i) \oplus 1$$

$$i = 1, 2, \cdots, k-1, k.$$

The relation between $d(1),\ d(2),\ \cdots,\ d(k-1),\ d(k)$ and symbols in left is

$$d(i) = f(1,i) \oplus f(2,i), \cdots, \oplus f(k-1,i) \oplus f(k,i) \oplus 1$$

$$i = 1, 2, \cdots, k-1, k.$$

where

$$f(j,i) = x(j, ((i+j-2) \bmod k) + 1)$$

$$j = 1, 2, \cdots, k-1, k.$$

To extend the function of quantizer, soft-decision decoding[3,13] is selected according to the MA code. Because of the noise character in holographic storage scheme, but parameters of noise are not constant. So the log-likelihood ratio $L(u|y)$[4] is very difficult to calculate accurately. To make full use of the information included in received data, a new soft-decision $S(u|y)$ is redefined. u can be judged as 1 or 0 by the polarity of $S(u|y)$, and can know its reliability from the $|S(u|y)|$. Thus we can deduce

$$S(u|y) = \begin{cases} c_1 y & \text{if we judge } u = 1 \\ c_0(\mathrm{Max} - y) & \text{if we judge } u = 0 \end{cases}, \quad (1)$$

where c_1, c_0 are the polarities of $S(u|y)$ while u is judged as 1 or 0, specially $c_1 \times c_0 = -1$. Max is the maximum of received pseudo-analog signal y. The process of deducing the formula above is described in Ref. [11].

From above description, it can be found that the $S(u|y)$ is calculated easily and can be modified by the information of modulation code. Thus the $S(u|y)$ can accurately represent the information contained in the pseudo-analog signal. This is another merit of using MA code. Then a new iterative decoding algorithm can base on those soft values. The techniques of encoding and decoding are described in detail in Ref. [11].

Our experiments have been done in a DHSS with traditional 90° angle-multiplexing architecture. The experiment setup is shown in Fig. 6.

An experiment setup with holographic storage and retrieval was conducted. In the experiment, a segment of multimedia data, including video and audio data, was encoded into twenty-five pages of holograms.

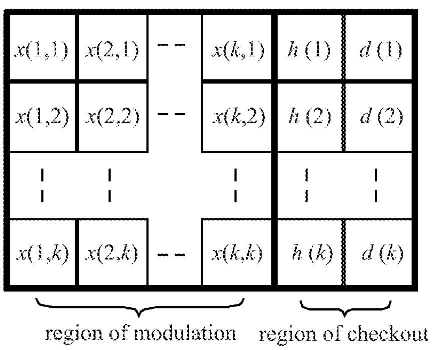

Fig. 5. Structure of MA.

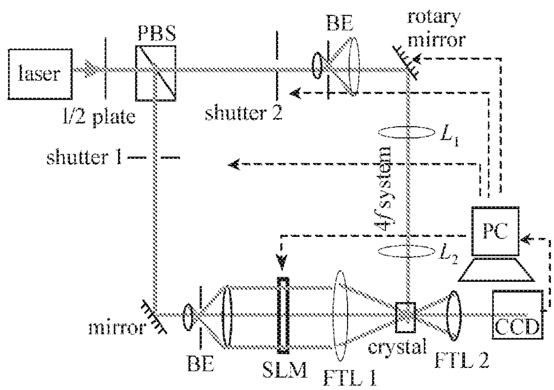

Fig. 6. Holographic storage setup. PBS: polarization beam splitter; BE: beam expander; SLM: spatial light modulator; FTL: Fourier transform lens; PC: personal computer; CCD: detector array.

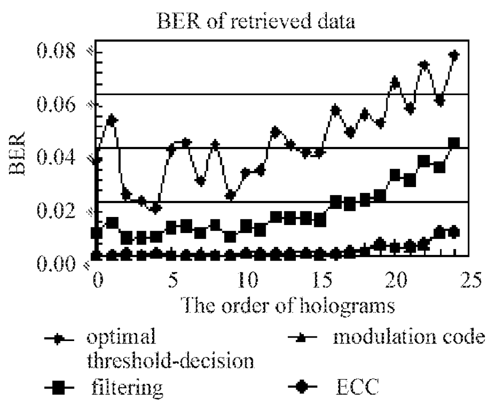

Fig. 7. BER after processing by some DSP.

Some DSP methods described above were adopted during the process. BER after processing by them was shown respectively in Fig. 7. It can be seen that the functions of filtering and MA code are very evident, especially the MA code. Because by using MA code the quantizer does not work alone, its soft-decision decoding has been tightly integrated with decoder of modulation codes and parts of decoder of ECC. It can be seen from the experiment that when the BER is higher than a certain value, the effect of MA is better than that of traditional modulation code evidently. In fact, when the raw BER is lower than 1×10^{-2} the result of MA code is already very evident[11]. In a word, the MA code benefits to the system of high BER, for instance, the DHSS.

Though there were some bit-errors in data retrieved by the scheme, the retrieved multimedia data was replayed successfully.

All DSP methods used in the scheme are compatible. The 2-D cyclic shifting interleaving reduces the influence of Burst error. $(2N-1)\times(2N-1)$ minimum mean square error 2-D equalizer can restrain the ISI which is very severe in holographic storage. Especially the MA code takes advantage of the constant weight code, ECC and iterative decoding. The MA code and the soft-decision according to it can make full use of the information of data in the process of decoding. They can effectively remove the noise in DHSS. The success of replaying multimedia data retrieved can prove that the holographic storage scheme based on DSP is feasible. The elementary success of the scheme can lay the foundation for further research in holographic storage.

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References

1. J. Ashley, M. P. Bernal, G. W. Burr, H. Coufal, H. Guenther, J. A. Hoffnagle, C. M. Jefferson, B. Marcus, R. M. Macfarlane, R. M. Shelby, and G. T. Sincerbox, IBM J. Res. Develop. **44,** 341 (2000).
2. G. W. Burr, H. Coufal, J. A. Hoffnagle, C. M. Jefferson, M. Jurich, R. M. Macfarlane, and R. M. Shelby, Asian J. Physics **10,** 121 (2001).
3. W. Chou and M. A. Neifeld, J. Opt. Soc. Am. A **18,** 185 (2001).
4. J. Hagenauer, E. Offer, and L. Papke, IEEE Trans. Info. Theory **42,** 429 (1996).
5. W. Wu, Acta Electron. Sin. **26,** 35 (1998).
6. Z. Ye and V. Wei, Acta Electron. Sin. **26,** 41 (1998).
7. M. Blaum, J. Bruck, and A. Vardy, IEEE Trans. Info. Theory **44,** 730 (1998).
8. W. Chou and M. A. Neifeld, Appl. Opt. **37,** 6951 (1998).
9. G. W. Burr, W. Chou, M. A. Neifeld, H. Coufal, J. A. Hoffnagle, and C. M. Jefferson, Appl. Opt. **37,** 5431 (1998).
10. M. A. Neifield, K. M. Chugg, and B. M. King, Opt. Lett. **21,** 1481 (1996).
11. S. Dun, K. Jia, M. Qin, and S. Tao, Proc. SPIE **4930,** 138 (2002).
12. G. W. Burr, J. Ashley, H. Coufal, R. K. Grygier, J. A. Hoffnagle, C. M. Jefferson, and B. Marcus, Opt. Lett. **22,** 639 (1997).
13. V. Vadde and B. V. K. Vijaya Kumar, Opt. Lett. **24,** 546 (1999).
14. J. Hagenauer, IEEE Trans. Commun. **43,** 2449 (1995).