4/6 Modulation Code for Multi-level Holographic Data Storage

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Abstract: Holographic data storage system has good characteristics of high recording density, transfer rate, and short access time. On the other hand, it has a serious problem of two dimensional inter-symbol interference. Furthermore, because one pixel can save more than 1 bit per pixel in multi-level HDS, the storage system has small noise margin for symbol detection that causes more errors. In this paper, we propose a 4/6 modulation code which mitigates two dimensional inter-symbol interference for multi-level HDS. The proposed code shows better BER performance than that of the 2/3 and 6/9 modulation code in a poor channel environment, such as large blur and misalignments.

Keywords—**Holographic data storage, 2D-ISI, multi-level, modulation code**

1. Introduction

Multi-level holographic data storage (HDS) has attracted much attention as a next generation data storage system [1, 2] because more than 1 bit can be stored in one pixel. HDS has an advantage of large capacity, high data transfer rate, and fast access time. The principle of HDS is the multiplexing of data pages into a volume of holographic medium. The signal beam of data is changed by a spatial light modulator (SLM), and the interference fringe formed by the interfering reference beam is recorded in the hologram media. Reversely, when reading, the reference beam is incident on the holographic media and the information page signal is extracted. However, HDS is affected by inter-page interference (IPI) and two-dimensional inter-symbol interference (2D-ISI) between adjacent symbols. IPI is caused by reading and writing processes [3, 4]. Since multiple images are stored in the same holographic space, Inter-page interference (IPI) occurs. To reduce the IPI, the intensity of each page must be maintained in a same ratio. 2D-ISI occurs since the data are read by charge-coupled device (CCD). 2D-ISI negatively affects the HDS performance. To obtain good performance, researchers have investigated detection algorithms and ECCs [5-7].

For multi-level HDS system, since one pixel contains more than 1 bit, the system is more vulnerable to the error. Figure 1 shows an example of serious ISI in 4-level HDS. When the smallest symbol of 0 and the largest symbol of 3 are side by side in any direction, ISI become a severe problem. Therefore, this situation is avoided by using an appropriate modulation code. Some modulation processes to avoid 2D-ISI and IPI have been proposed [8-13]. This paper propose a 4/6 modulation code having minimum distance for 4-level HDS in order to reduce 2D-ISI. And, we compare the performance of the proposed, 2/3, 6/9 modulation having the same code rate.

2. Proposed 4/6 Modulation Code

2. 1 Modulation procedure

The proposed code can mitigate 2D-ISI. Since one pixel represents 4 symbols in 4-level HDS, one pixel can save 2 bits. Figure 2 illustrates a structure of modulation scheme. We modulate from four input symbols (8 bit) to six output pixels (3 by 2 array). P1, P4, and P5 pixels of the modulated codeword can have {1, 2} symbols, and P2, P3, P6 pixels can have {0, 1, 2, 3} symbols. The number of such codewords is 512 (=2×4×4×2×2×4), because p1, p4, and p5 can have 2 symbols, and p2, p3, and p6 can have 4 symbols. Furthermore, each codeword of the proposed code is selected for the Euclidean minimum distance of 2 starting from (1, 0, 0, 1, 1, 0) to (2, 3, 3, 2, 2, 3). The number of selected codewords is 256.

Figure 3 shows an example of consititution of modulation code. Fig. 3a displays a situation of neighboring the largest and the smallest symbols. For example, P6 has symbol of 3, and P2 has symbol of 0. This situation has problem about neighboring the largest symbol and the smallest symbol. To prevent this case, we proposed an array method in accordance with line. Odd lines retain the (P1, P2, P3, P4, P5, P6) codewords, and even lines maintain the (P2, P1, P4, P3, P6, P5) codewords, which is illustrated in Fig. 3b. Using the proposed modulation code, the largest symbol does not lie next to the smallest symbol in any direction, and thus major ISI is avoided. Also, the Euclidean distance between any two codewords is greater or equal to 2. The code rate of the 4/6 modulation code is 0.66, and each pixel saves 1.33 bits/pixel (8bit/6pixel).

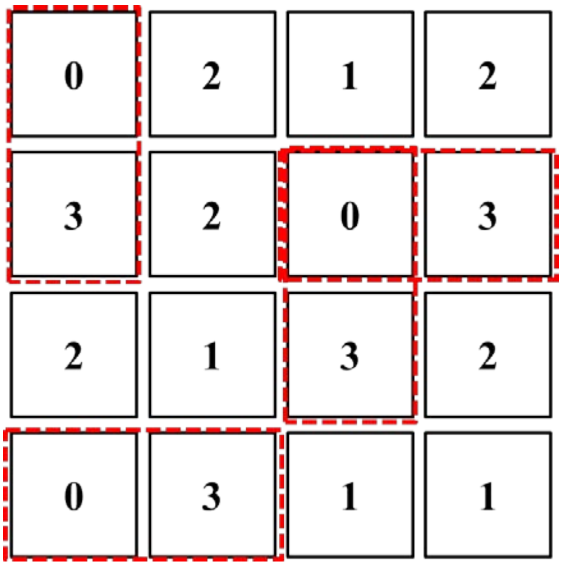

Figure 1. Example of serious ISI in 4-level HDS.

Table 1. The codewords of the proposed 4/6 modulation code.

Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol	Codeword Number	symbol
0	100110	32	110111	64	120110	96	130111	128	220111	160	230110	192	200111	224	210110
1	100112	33	110113	65	120112	97	130113	129	220113	161	230112	193	200113	225	210112
2	100121	34	110120	66	120121	98	130120	130	220120	162	230121	194	200120	226	210121
3	100123	35	110122	67	120123	99	130122	131	220122	163	230123	195	200122	227	210123
4	100211	36	110210	68	120211	100	130210	132	220210	164	230211	196	200210	228	210211
5	100213	37	110212	69	120213	101	130212	133	220212	165	230213	197	200212	229	210213
6	100220	38	110221	70	120220	102	130221	134	220221	166	230220	198	200221	230	210220
7	100222	39	110223	71	120222	103	130223	135	220223	167	230222	199	200223	231	210222
8	101111	40	111110	72	121111	104	131110	136	221110	168	231111	200	201110	232	211111
9	101113	41	111112	73	121113	105	131112	137	221112	169	231113	201	201112	233	211113
10	101120	42	111121	74	121120	106	131121	138	221121	170	231120	202	201121	234	211120
11	101122	43	111123	75	121122	107	131123	139	221123	171	231122	203	201123	235	211122
12	101210	44	111211	76	121210	108	131211	140	221211	172	231210	204	201211	236	211210
13	101212	45	111213	77	121212	109	131213	141	221213	173	231212	205	201213	237	211212
14	101221	46	111220	78	121221	110	131220	142	221220	174	231221	206	201220	238	211221
15	101223	47	111222	79	121223	111	131222	143	221222	175	231223	207	201222	239	211223
16	102110	48	112111	80	122110	112	132111	144	222111	176	232110	208	202111	240	212110
17	102112	49	112113	81	122112	113	132113	145	222113	177	232112	209	202113	241	212112
18	102121	50	112120	82	122121	114	132120	146	222120	178	232121	210	202120	242	212121
19	102123	51	112122	83	122123	115	132122	147	222122	179	232123	211	202122	243	212123
20	102211	52	112210	84	122211	116	132210	148	222210	180	232211	212	202210	244	212211
21	102213	53	112212	85	122213	117	132212	149	222212	181	232213	213	202212	245	212213
22	102220	54	112221	86	122220	118	132221	150	222221	182	232220	214	202221	246	212220
23	102222	55	112223	87	122222	119	132223	151	222223	183	232222	215	202223	247	212222
24	103111	56	113110	88	123111	120	133110	152	223110	184	233111	216	203110	248	213111
25	103113	57	113112	89	123113	121	133112	153	223112	185	233113	217	203112	249	213113
26	103120	58	113121	90	123120	122	133121	154	223121	186	233120	218	203121	250	213120
27	103122	59	113123	91	123122	123	133123	155	223123	187	233122	219	203123	251	213122
28	103210	60	113211	92	123210	124	133211	156	223211	188	233210	220	203211	252	213210
29	103212	61	113213	93	123212	125	133213	157	223213	189	233212	221	203213	253	213212
30	103221	62	113220	94	123221	126	133220	158	223220	190	233221	222	203220	254	213221
31	103223	63	113222	95	123223	127	133222	159	223222	191	233223	223	203222	255	213223

2. 2 Demodulation procedure

The Euclidean distance is calculated between the received codeword r=(r_0, r_1, r_2, r_3, r_4, r_5) and each codeword pattern p_n=(p_0, p_1, p_2, p_3, p_4, p_5) for n=0, 1, ..., 255, respcetively. d_n is calculated by

$$d_n = \sum_{k=0}^{5}(r_k - p_k)^2 \tag{1}$$

where n=0, 1, ..., 255. After that, the codeword p_n having minimum d_n is selected as the decoded codeword. The message word corresponding to the decoded codeword p_n is outputted.

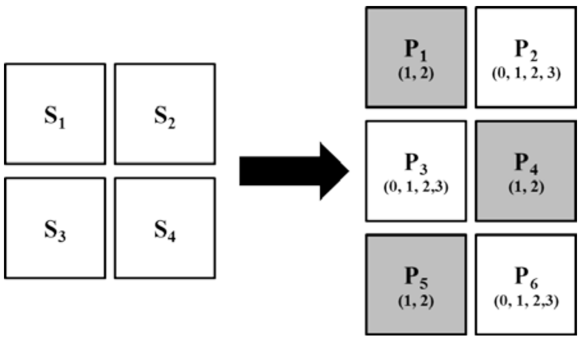

Figure 2. Structure of the proposed modulation scheme.

3. Simulation Results

We simulate a holographic channel model that relates input data to the output data pixels through the CCD array [14, 15]. Suitable reference beam interprets the data retrieval. Using the CCD array can detect the resultant signal. Continuous point-spread function is modeled by

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

where m_x and m_y are x- and y-axis misalignment, respectively, σ_b is the blur of the signal that has been distributed, and sinc(x,y)=sin(sin(πx)/ πx) sin(sin(πy)/ πy). While we can store more data when the σ_b is increased, the interference between the adjacent symbols is also increased. Thus, bit error rate (BER) performance becomes worse. The discrete point spread function can be defined as follow

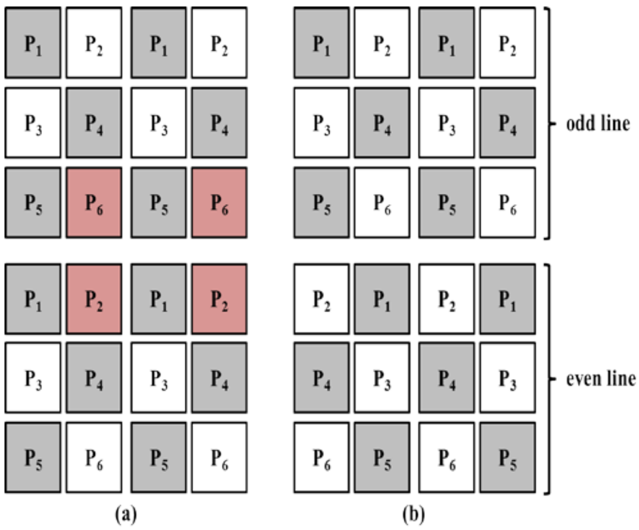

Figure 3. Constitution of modulation code.

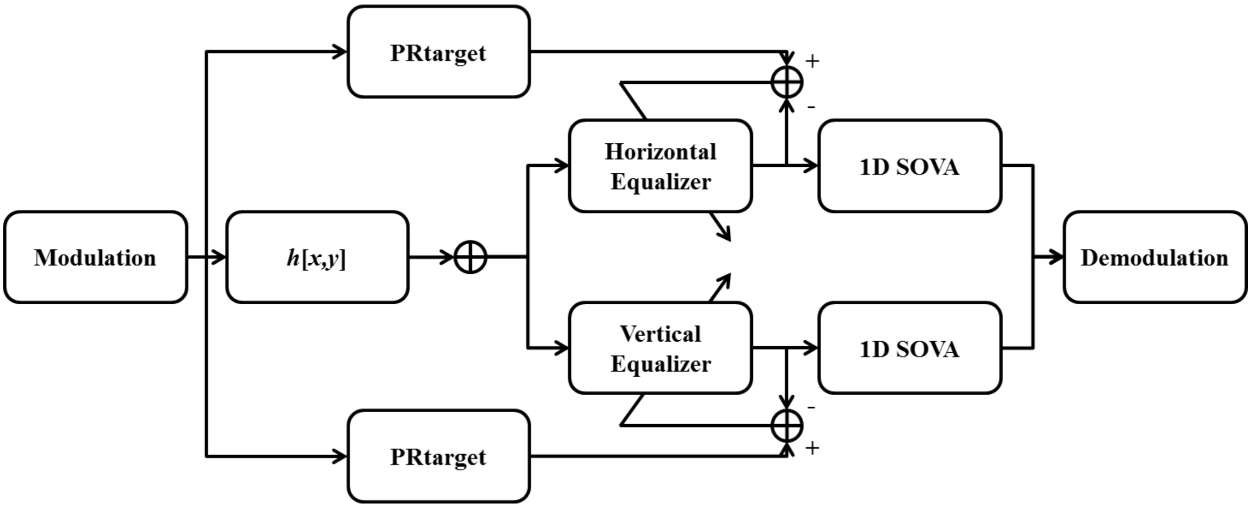

Figure 4. Block diagram of the proposed modulation.

$$h[p,q]=\int_{q-\alpha/2}^{q+\alpha/2}\int_{p-\alpha/2}^{p+\alpha/2}h(x,y)dxdy \quad (3)$$

where α is the linear fill factor of the CCD pixels. The signal $r[p,q]$ that has passes through the channel is given by

$$r[p,q]=d[p,q]*h[p,q]+n[p,q] \quad (4)$$

where $d[p,q]$ is the input data, * indicates two-dimensional convolution operation, and $n[p,q]$ expresses additive white Gaussian noise (AWGN). We simulated 1,000 pages, and each page has a size of 1024×1024 pixels. We also define the signal-to-noise ratio (SNR) as $10\log_{10}(1/\sigma^2)$ assuming noise variance σ^2. Figure 4 shows the block diagram of the proposed modulation code for HDS. The simulation employs the equalizer and soft-output Viterbi algorithm (SOVA). The coefficients of the equalizer are updated by the least mean square (LMS) algorithm. The equalizer adapts the channel to the PR (131) target.

Figure 5 displays BER performance according to SNR. The blur is 1.0 and the x- and y-axis misalignments are 10% and 10%, respectively. We compare a random data, 2/3 modulation code [16], 6/9 modulation code [17], and the proposed 4/6 modulation code. Three modulation codes have the same code rate of 0.66. At the BER of 10^{-5}, the proposed modulation code performs about 7dB, 4dB, and 4dB better than random data, 6/9, and 2/3 modulation code, respectively, because the proposed modulation code has larger minimum distance compared to the others. Figure 6 illustrates BER performance in accordance with SNR. The blur is 1.1 and the x- and y-axis misalignments are 0% and 0%, respectively. The proposed modulation code performs better than 2/3 and 6/9 modulation code.

4. Conclusion

In this paper, we have introduced a four-level 4/6 modulation code for HDS. The proposed modulation removes the fatal 2D-ISI patterns and shows better performance than the same code rate of 2/3 and 6/9 modulation codes.

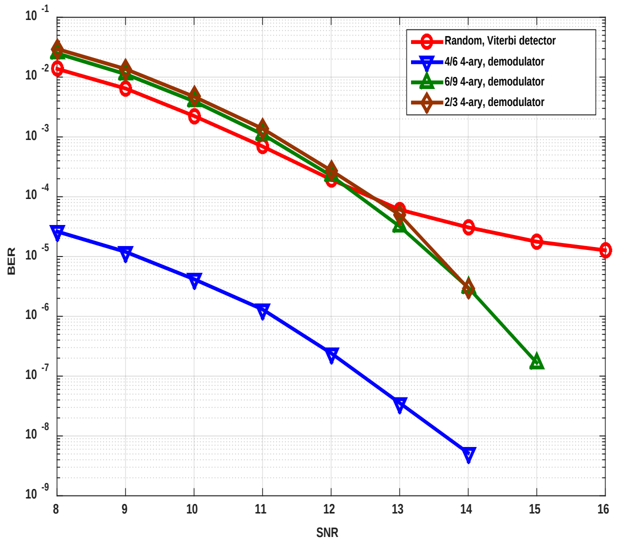

Figure 5. BER performance when the blur is 1.0 and the x- and y-axis misalignments are 10% and 10%, respectively.

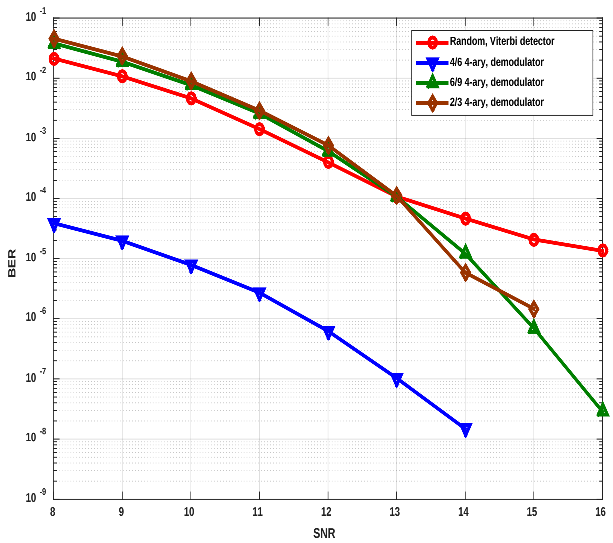

Figure 6. BER performance when the blur is 1.1 and the x- and y-axis misalignments are 0% and 0%, respectively.

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