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엇갈린 형태의 비트 패턴드 미디어 기록장치를 위한 오류정정능력을 갖는 7/10 변조부호

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Error-Correcting 7/10 Modulation Code for Staggered Bit-Patterned Media Recording Systems

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요 약

비트 패턴드 미디어 기록장치는 하나의 자기 입자에 1비트를 저장할 수 있는 차세대 기술로 주목받고 있다. 비트 패턴드 미디어 기록장치에서 기록밀도를 증가시키기 위해서는 아일랜드들 간의 간격이 좁아져야하지만 이는 2차원 인접 심볼간 간섭을 증가시킨다. 따라서, 비트 패턴드 미디어 기록장치의 비트 오류율은 2차원 인접 심볼간 간섭으로 인해 성능이 저하된다. 본 논문에서는 오류정정능력을 갖는 7/10 변조부호를 제안한다. 제안하는 변조부호는 7비트의 입력 데이터를 10비트의 코드워드로 변조한다. 제안하는 변조부호는 고립 픽셀 패턴을 제거 할 수 있으며, 코드워드간 최소 거리가 2이상인 특징을 가지고 있다. 또한 엇갈린 형태의 비트 패턴드 미디어 기록장치에 알맞도록 고안되었다. 제안하는 변조부호는 변조부호를 사용하지 않았을 때보다 좋은 결과를 보여주었다.

키워드 : 비트 패턴드 미디어 기록 장치, 데이터 저장장치, 오류 정정, 변조부호, 트렐리스 변조부호
Key Words : Bit-patterned media recording, data storage system, error-correcting, modulation code, trellis modulation code

ABSTRACT

Bit-patterned media recording (BPMR) is a potential future technology to record data in magnetic islands (one bit per island). In BPMR systems, to increase the areal density, the distance between adjacent islands must be reduced. Since leading to two-dimensional (2D) interference increased significantly. The bit error rates performance of BPMR systems is seriously decreased due to the emergence of 2D interference. This paper presents an error-correcting 7/10 modulation code. This modulation converts 7-bit data to 10-bit group symbols. Each these symbol have two properties include avoid isolate inter-symbol interference between neighbor islands and archives minimum distance Hamming of 2. Besides, we designed this modulation code to fit into a staggered-array BPMR layout, which helps BPMR systems overcome the limits of the high areal density. The results of the simulation show that the BPMR system with the proposed modulation code better than the system without the modulation code.

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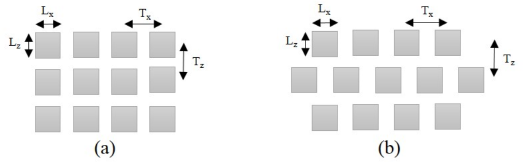
Ⅰ. Introduction

In magnetic recording systems, superparamagnetic phenomena are the most important obstacle, that prevents conventional magnetic recording systems from reaching an areal density (AD) beyond 1 tera bits per square inch (Tb/in^2)[1]. In particular, bit-pattern media recording (BPMR) is a promising technology that can achieve the AD up to 4 Tb/in^2. To continue increasing the AD in the BPMR system, the distance between the islands needs to be reduced. This results in increased two-dimensional (2D) interference. This 2D interference includes inter-symbol interference (ISI), which occurs when the distance between islands in the along-track direction is narrowed, and inter-track interference (ITI), which appears when the distance of islands in the across-track direction is narrowed. To tackle the 2D interference, several 2D coding schemes have recently been proposed[2-5]. However, the above schemes are applied to regular-array BPMR [see Fig. 1(a)] but not suitable for staggered-array BPMR [see Fig. 1(b)]. Therefore, we propose a 7/10 modulation code for staggered-array BPMR. This modulation code has the codeword that satisfies two properties. The first property is that the codeword ensures a minimum Hamming distance of 2. The other is that the codeword avoids the isolated phenomenon. From there, we apply the trellis modulation scheme to further enhance the error correction process in the decoding process. Simulation results show that the proposed modulation code can improve the bit error rate (BER).



(a) (b)

그림 1. BPMR의 배열 구조 (a) 일반적 형태, (b) 어긋난 형태
Fig. 1. The structure of (a) is regular-array BPMR and (b) is staggered-array BPMR.

Ⅱ. Proposed Modulation Code

To create the codeword we classify two cases described in Fig. 2. The bounding shape of the 1st and 3rd columns are the same and they are odd columns. Another case is the bounded area of even columns (2nd and 4th columns). The proposed modulation code converts a sequence of 7 bits of user data into a 10-bit codeword in the forms shown in Fig. 3. In Fig. 3, from the codeword form of even columns to get the codeword shape of the odd columns we perform a 180-degree rotation of the codeword shape of the even column. We have 7 bits of user data, so we need 2^7=128 symbols for the proposed modulation code. To achieve a minimum distance Hamming of 2, we choose codeword with the number of 1s of 0, 2, 4, 6, 8, and 10. These symbols are shown in Fig. 3.

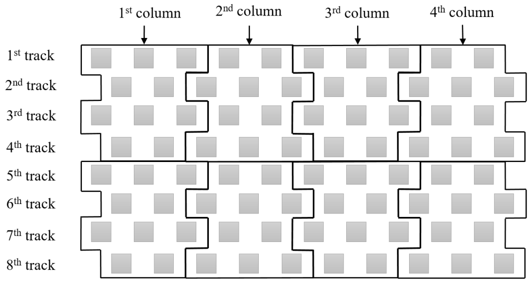


그림 2. 코드워드 구조 예제
Fig. 2. Partitioning of data creates codeword.

2.1 Encoding

In this study, we propose two modulation methods as follows:

Modulation 1: A 7-bit input (0000000-1111111) is assigned to a 10-bit codeword (C0-C127) using a one-to-one mapping algorithm. To implement this algorithm, in our study we use lookup tables. For example, if the input bits are 0100101, they are converted into a codeword C37 through a codeword-mapping table.

Modulation 2: We apply the trellis modulation structure shown in Table 1. In the table, we assign "oc" to "output codeword" and "ns" to "next state". In this structure, we consider 128 states and only one branch between the current state and the next

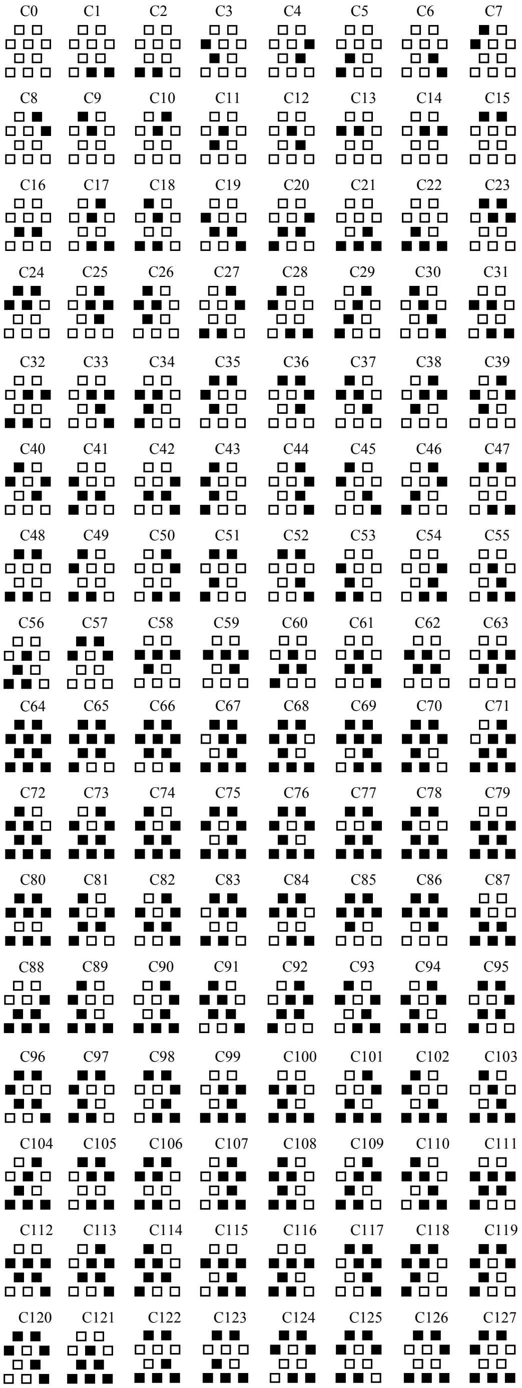


그림 3. 선택된 코드워드 집합
Fig. 3. The codeword.

state. In state S0, the branches labeled 0, 1, 2, ..., 127 are assigned the codeword C0, C1, C2, ... , C127, respectively. Similarly, in the state Sk, branches labeled 0, 1, 2, ..., 127 are assigned the codeword C(k mod 128), C(k+1 mod 128), ... , C(k+127 mod 128). respectively. The encoding process starts at state S0. The encoding process takes 7 input bits, generates 10-bit codeword at the output and move to the next state. After producing *m* codeword (synonymous with *m*+1 status), a word parity is added to return the status to S0. This process continues until no input data remain. Thus, the actual code rate becomes 7*m*/10(*m*+1), where *m* is the interval between the terminating parity symbols. Fig. 4 shows an example of the encoded sequence.

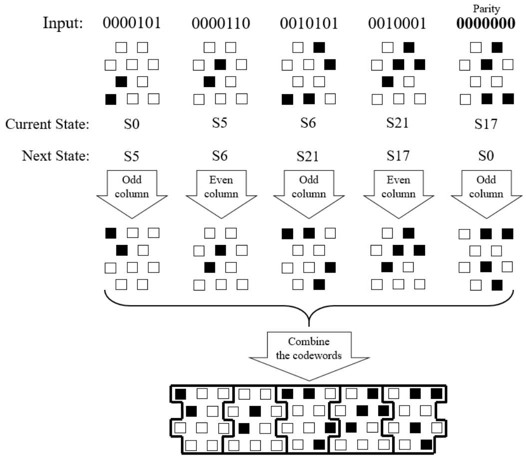


그림 4. 두 번째 변조방식의 예제
Fig. 4. Example of the modulation 2.

2.2 Decoding

Modulation 1: We compare the codeword received with the codeword in the table by calculating the Euclidean distance (ED) and choose the codeword that has the smallest ED[6].

Modulation 2: We use the Viterbi algorithm (VA) with ED as the branch metric to implement the decoding scheme. Therefore, the branch metric is calculated by

$$\lambda_i(s_a, s_b) = \sum_{j=1}^{10} \left[z_{ji} - u_{ji}^{(k)}(s_a) \right]^2 \qquad (1)$$

where s_a is the current state, s_b is the next state, z_{ji} is the *j*th bit of the *i*th received codeword, and $u_{ji}^{(k)}$

is the *j*th bit of the *i*th branch codeword of the *k*th possible transmitted codeword for *k*=0, 1, ..., 127. When the process reaches the *m*th codeword, which corresponds to cumulative metric. Then, the decoding procedure outputs the message word corresponding to each surviving branch. This process is continues until no codeword is received. An example of the decoding process is shown in Fig. 5.

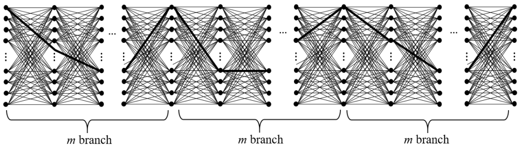


그림 5. 제안하는 변조부호의 디코딩 예제
Fig. 5. Decoding example of the proposed modulation code.

Ⅲ. Simulation and Results

The user bits $a[k]\in\{0, 1\}$ are put into the proposed 7/10 modulation codewords, which consist of 2D islands $s[k,j]\in\{-1, 1\}$. The output codewords from the modulation block are transmitted over the BPMR channel with AWGN[7,8]. Channel outputs $y[k,j]$ are entered to 2D equalization block[9]. The equalizer used has a size of 5 × 5; the coefficients of the PR target polynomials are $f_h(0.1, 1, 0.1)$ for across-tracks. Then, the output $z[k,j]$ from the 2D equalizer is put into the SOVA detector to reduce 2D ISI and recover the data $\hat{s}[k,j]$. Finally, the original input data $\hat{a}[k]$ is recovered by decoding the data $\hat{s}[k,j]$. We define the channel signal-to-noise ratio (SNR) as $10\log_{10}(1/\sigma_w^2)$, where σ_w^2 is the AWGN power.

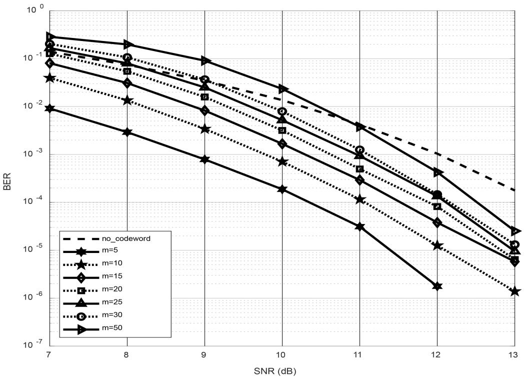


그림 6. *m*에 따른 변조부호의 BER 성능
Fig. 6. BER performance according to *m* value.

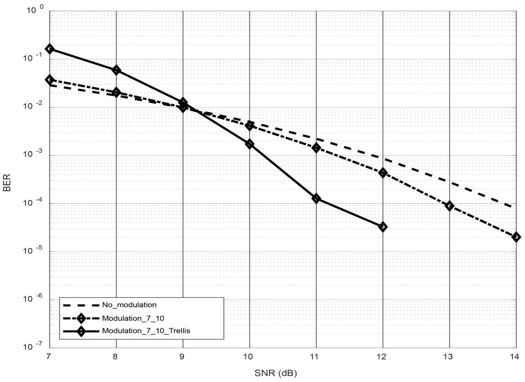


그림 7. 기록밀도 2 Tb/in^{2}에서 변조부호를 사용하지 않았을 때와 기록밀도가 3 Tb/in^{2}에서 변조부호를 사용하였을 때 BER 성능 비교
Fig. 7. BER performance at the ADs of 2 Tb/in^2 (system without coding), and 3 Tb/in^2 (system with code rate 7/10).

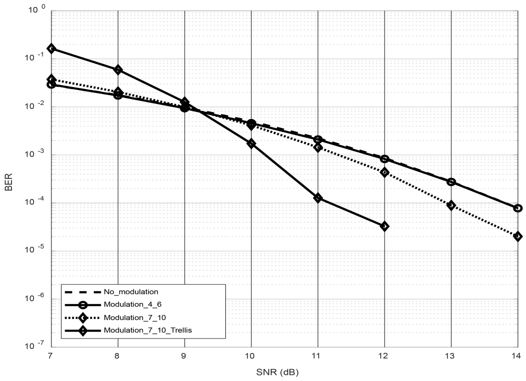


그림 8. 4/6 변조부호와 7/10 변조부호의 성능 비교
Fig. 8. Compare BER performance between system with code rate 4/6 and system with code rate 7/10.

First, we examine the value of *m* affects the bit error rates (BER) performance in Fig. 6. With an error bit in a block *m* codeword, we can fix this bit error, when we apply the Viterbi algorithm (VA) on this block. If the value of *m* decreases, we have more *m* codeword blocks. Since we can fix more error bits. Therefore, the BER performance depends on the value of *m*. In this experiment, we simulated 110 pages with 1200 × 1200 bits size, consist of 10 pages to train the equalizer coefficients. We simulated the system without coding at an AD of 2 Tb/in^2 (T_x = T_y = 18 nm) and the system with coding at an AD of 3 Tb/in^2 (T_x = T_y = 14.5 nm).

The results showed that the code rate decreases when the value of m increases. At values of m above 30, the BER performance does not change significantly. From here we will set the value of m = 30.

In Fig. 7, we simulate 7/10 simulation with method 1 and method 2. In this experiment, we changed the AD to ensure the user data remains constant in the constant area. The system without coding uses an AD of 2 Tb/in^2 (T_x = T_y = 18 nm). The system with the 7/10 code rate is simulated at the AD of 3 Tb/in^2 (T_x = T_y = 14.5 nm). The results showed that the proposed 7/10 modulation code using a one-to-one mapping algorithm has an approximately 1 dB gain at 10^{-4} BER. On the other hand, as using trellis modulation, the gain at 10^{-4} BER is approximately 3 dB gain.

In the next simulation, we compare our proposed modulation code with a 4/6 modulation code, which applies to the holographic data storage systems[10]. The BER performance of this simulation is shown in Fig. 8. Here, the modulation with a 4/6 code rate and our proposed modulation code are simulated at the AD of 3 Tb/in^2. The system without coding is simulated at the AD of 2 Tb/in^2. The results showed that the proposed modulation code better than the 4/6 modulation code.

Ⅳ. Conclusion

We have proposed the error-correcting 7/10 modulation code for staggered-array BPMR. By creating a structure suitable for staggered-array BPMR, our proposed modulation code achieved a high code rate. At the same time, our codeword not only eliminates fatal 2D ISI patterns but also ensures the minimum Hamming distance of 2. Since the trellis modulation coding scheme is applied to correct errors. In general, the results indicate that the system with our proposed modulation code archives higher coding gain than systems without coding. In particular, our proposed modulation code provides a coding gain of approximately 3 dB compared to the random signal at 10^{-4} BER.

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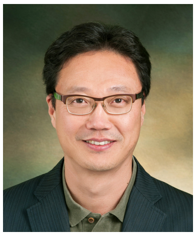

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