Performance Improvement of Optical Satellite Communications by Interleaved IEEE 802.11 LDPC

Duy Thong Nguyen, Youngil Park
Department of Electronics Engineering, Kookmin University
77 Jeongneung-ro, Seongbuk-gu, Seoul 136-702, Korea
thongnguyenduy88@gmail.com, ypark@kookmin.ac.kr

***Abstract*—Optical wireless communication using a laser is a strong candidate for the next generation satellite communications due to its large bandwidth. However, the channel environment of satellite communications is very tough, suffering from fading by atmospheric turbulence. Therefore, a powerful channel coding such as low-density parity check (LDPC) code is required for error correction. In this paper, the performance of a LDPC code is evaluated in this harsh channel environment. At the same time, in order to improve the system performance further, an interleaving method in combination with a LDPC code is used to overcome the burst error problem, which frequently occurs in optical satellite communication systems (OSC). Simulation results show that 970 consecutive burst error bits can be recovered by using a large size LDPC code and the proposed type of interleaving.**

Keywords— Low-density parity check (LDPC), optical satellite communication (OSC), optical wireless communication (OWC), hard decision, burst error, interleaving

I. INTRODUCTION

In response to the ever-increasing number of high-quality services, the 100 Gigabit Ethernet has been standardized and 200 Gigabit and 400 Gigabit standard are planned in the future [1]. Communication based on the laser is a very efficient way to deliver signals at this high data rate. Furthermore, Radio Frequency (RF) communications have become overloaded for sending data in space (e.g., because of high-quality services, limitation of bandwidth, etc.). In recent years, Optical Wireless Communications (OWC) [2] has emerged as a new technology which can replace traditional RF technology. Due to its outstanding performance, high speed, and unlimited bandwidth, it is expected that OWC will replace RF technology in the near future.

However, the use of OWC in satellite communication systems also has many obstacles such as the long distance, atmospheric turbulence (e.g., rain, wind, clouds, snow, temperature, ambient light, etc) or other abnormal weather conditions, as illustrated in Fig. 1. Therefore, to ensure the stability of the transmission channel, the transmission power is required to increase, but, the power supply of satellite is always limited. Thus, an efficient coding scheme should be used to deal with the atmospheric turbulence and improve the performance of the system.

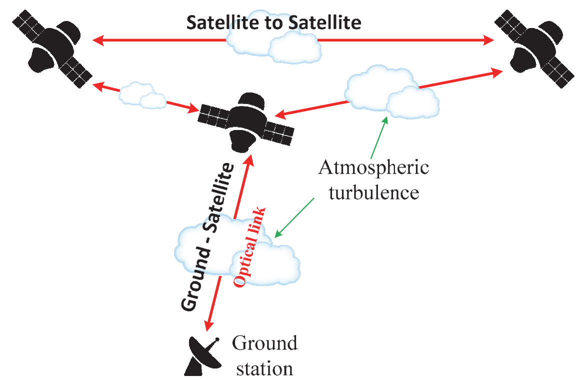

Fig. 1. Channel environment of optical satellite communication systems

A few decades ago, Turbo code was known to be the best code to improve channel performance. However, in recent years, LDPC codes become popular and are used in many applications. LDPC codes have shown that an iterative LDPC decoder based on the sum-product algorithm (SPA) can achieve a performance of 0.0045dB close to the Shannon limit [3]. Along with Turbo codes, LDPC codes are considered to be the future of Forward Error Correction (FEC) in optical communications. The LDPC scheme in the IEEE 802.11n standard is a form of LDPC codes with specific parity check matrices that were effective in the Wi-Fi and WiMAX systems [4]. In this paper, Binary Phase Shift Keying (BPSK) modulation is adopted, that has two specific phases 0 and π , standing for ‘1’ and ‘0’, respectively. It is demonstrated that the BPSK can obtain higher performance than On-Off Keying modulation [5]. Simultaneously, we use a specific parity check matrix in 802.11 standards and interleaved technique to improve the performance of OSC system.

The rest of the paper is presented as follow: Section II describes the LDPC codes in brief, and the idea of interleaving is suggested. And the system model is explained in this section. Finally, the simulation results are shown in the Section. III.

II. SYSTEM ANALYSIS

A. LDPC codes in brief

LDPC codes were originally invented by Gallager in 1960s

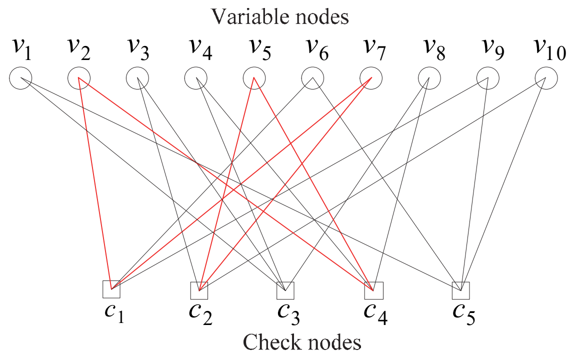

Fig. 2. Tanner graph to represent the LDPC code

[6]. Like other block codes, LDPC code is represented by a parity-check matrix $H(m\times n)$ which has low density of 1's as in (1). The generator matrix $G(k\times n)$ is generated from H matrix, where $k=m-n$ is the length of information. Regular LDPC codes consist of exactly w_c 1's in each column and exactly $w_r = w_c(n/m)$ 1's in each row. The code rate $R=k/n$ is related to these parameters via $R=1-(\mathrm{w}_c/w_r)$. An example of H matrix (5, 10) with $w_c=2$ and $w_r=4$ is shown in equation (1):

$$H=\begin{bmatrix}0&1&0&0&0&1&1&0&1&0\\0&0&1&0&1&0&1&0&0&1\\1&0&1&1&0&0&0&1&0&0\\0&1&0&1&1&0&0&1&0&0\\1&0&0&0&0&1&0&0&1&1\end{bmatrix} \tag{1}$$

One of the best ways to represent the LDPC matrix is the Tanner graph as shown in Fig. 2. It's a bipartite graph where nodes are connected by edges. There are two types of nodes in the Tanner graph: variable nodes v and check nodes c . A variable node v_i connects to check node c_j if and only if $H_{ij}=1$. A cycle length v of Tanner graph is indicated as the red line in Fig. 2 (e.g., in this case $v=6$). The minimum cycle length of the graph is called the girth of a Tanner graph. It should be larger than 4 to achieve high performance.

In satellite communication systems, the data rate is very high. Therefore, the large matrix should be used to achieve the high performance. However, the system complexity needs to be considered. The complexity of LDPC codes is estimated by the number of operations to accomplish the encoding and decoding process. To create the codeword, a generator matrix $G=[I\,P]$ must be created by converting H matrix in the form $[\mathrm{P}^T\ \mathrm{I}]$ via Gauss-Jordan elimination [7]. However, P matrix is not sparse and this method lacks sufficient structure to enable low-complexity encoding. The more efficient method is to convert H matrix into lower triangular form [8]. This method can reduce the degree of complexity since the matrix is still sparse after the conversion. Hence, it is effective for large matrices. This is also the type of LDPC matrix adopted in the 802.11 standards.

B. *Decoding of LDPC code*

Decoding of LDPC codes is performed through iterative processing based on a belief algorithm. The decoding process estimates codeword by calculating the probability iteratively, updating and exchanging messages in each edge which connects between variable nodes and check nodes. The decoding process stops when the parity-check condition $r_x'.\mathrm{H}^T=0$ is satisfied (r_x' is the received codeword after each iteration), or the number of iterations exceeded the initial value. Increasing the number of iterations can improve the system performance, but at the cost of the complexity of the system.

Two type of iterative decoding algorithm is the hard decision and the soft decision. Soft decision decoder can distinguish the real value between 0 and 1. Thus, an analog-digital converter is required if LDPC code is implemented in the hardware. Although it can achieve a high performance, it costs calculation time and hardware complexity. On the contrary, hard decision adopts the information of a single bit that is either '0' or '1'. Therefore, the hard decision is simple and easy to implement. However, the performance is lower than that of the soft decision. Therefore, to improve the performance of the hard decision, the proposed interleaving can be used. The main purpose of it is to overcome burst error, which is very common in OSC systems.

C. *Proposed interleaving of the LDPC matrix in 802.11 standard*

Specific 802.11 LDPC matrices are applied to many different wireless systems such as WiFi or WiMAX, and have been shown to be effective. It is expected to work well in wireless optical systems also. For Line of Sight (LOS) optical systems such as visible light communication (VLC), optical camera communication (OCC) and optical satellite communication (OSC), the transmitter and receiver are in view of each other. Therefore, any sort of obstacle between them causes errors. For example, assuming that the data rate of a communication system is 100 Mbps, then 100 Kbit of data will be lost when a burst error happens during 1 msec. This burst error is very difficult to recover even with an error correction code.

The LDPC parity check matrix in 802.11 standards is Quasi-cyclic LDPC matrix. It has the minimum Hamming distance and the girth of 6, 8, 10 and 12, which are demonstrated in [9-10]. The parity-check matrix of a QC-LDPC code has $M\times N$ sub-matrices as shown in equation (2).

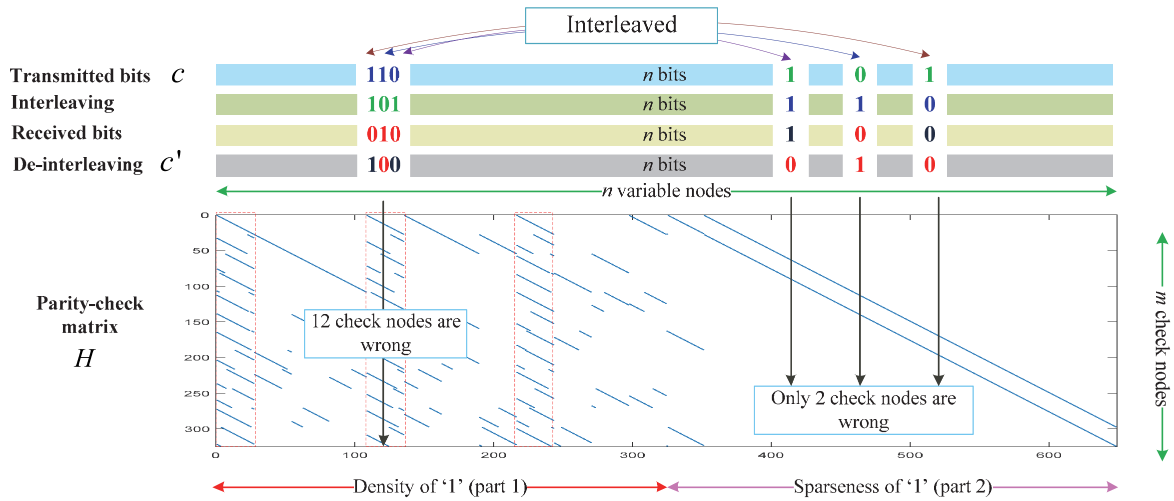

Fig. 3. The LDPC parity-check matrix in 802.11 standard

$$H = \begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} & \cdots & H_{1,\mathrm{N}} \\ H_{2,1} & H_{2,2} & H_{2,3} & \cdots & H_{2,\mathrm{N}} \\ . & . & . & & . \\ . & . & . & & . \\ H_{M,1} & H_{M,2} & H_{\mathrm{M},3} & \cdots & H_{M,\mathrm{N}} \end{bmatrix} \tag{2}$$

, where H_{ij} is a $Z \times Z$ sub-matrix in which row is a cyclic right shift of the row preceding it. Consequently, an LDPC parity-check matrix has a size of $MZ \times NZ$. An example of QC-LDPC matrix proposed in 802.11 standards with the data rate of 1/2 is shown in Table. I. An LDPC parity-check matrix of 802.11 standards is shown in Fig. 3. This matrix is created from the QC-LDPC matrix in Table. I, with the gap Z=27. The blue dots indicate the position of bit '1' in the matrix.

Obviously, the distribution of bit '1' in the H matrix is uneven. The data bits corresponding to the variable nodes, which connect to multiple check nodes will affect the output more than the other bits because a large number of check nodes are wrong

TABLE I. THE QC-LDPC MATRIX IS PROPOSED IN 802.11 STANDARD

0	–	–	–	0	0	–	–	0	–	–	0	1	0	–	–	–	–	–	–	–	–	–	–
22	0	–	–	17	–	0	0	12	–	–	–	–	0	0	–	–	–	–	–	–	–	–	–
6	–	0	–	10	–	–	–	24	–	0	–	–	–	0	0	–	–	–	–	–	–	–	–
2	–	–	0	20	–	–	–	25	0	–	–	–	–	–	0	0	–	–	–	–	–	–	–
23	–	–	–	3	–	–	–	0	–	9	11	–	–	–	–	0	0	–	–	–	–	–	–
24	–	23	1	17	–	3	–	10	–	–	–	–	–	–	–	–	0	0	–	–	–	–	–
25	–	–	–	8	–	–	–	7	18	–	–	0	–	–	–	–	–	0	0	–	–	–	–
13	24	–	–	0	–	8	–	6	–	–	–	–	–	–	–	–	–	–	0	0	–	–	–
7	20	–	16	22	10	–	–	23	–	–	–	–	–	–	–	–	–	–	–	0	0	–	–
11	–	–	–	19	–	–	–	13	–	3	17	–	–	–	–	–	–	–	–	–	0	0	–
25	–	8	–	13	18	–	14	9	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0
3	–	–	–	16	–	–	2	25	5	–	–	1	–	–	–	–	–	–	–	–	–	–	0

if an error bit occurs there. As shown in Fig. 3, the variable nodes in the red dashed line connect to the 12 check nodes, whereas the remaining variable nodes are connected to fewer check nodes. If a burst error occurs at the red part, the probability of data recovery is low.

The regular interleaving methods such as byte interleaving (i.e., data is packed in rows and sent in columns) [11] or permutation of random bits are almost ineffective when applied to LPDC code. It is because the ability of data recovery depends on the number of affected check nodes by noise, as is indicated by the number of bit '1' in equation (3). Also, as shown in Fig. 3, a lot of check nodes is affected when the error bits occur in part 1.

$$c'H^T = \begin{cases} [0,0,0,0,0,0,0,0,.....,0,0]_{1\times m}, & no\,error \\ [0,1,0,1,1,0,0,1,.....,0,1]_{1\times m}, & error \end{cases} \tag{3}$$

With a specific LDPC matrix in 802.11 standards, interleaving is performed by changing the position of the transmitted bits based on the parity-check matrix. In other words, the transmitted bits corresponding to the variable nodes, which connect to multiple check nodes will be dispersed at the different locations as shown in Fig. 3. Thus, if the burst error occurs, the number of affected check nodes will decrease as compared to the previous one.

III. RESULTS AND DISCUSSIONS

In the OSC system, the channel is influenced a lot by atmospheric turbulence. It degrades the quality of the received signal; as a result, the signal is often completely lost at a specific time. In [12], the effect of this fading is considered and evaluated. In addition, white noise combined with the burst error degrades the quality of signal a lot. The burst error is considered to be a serious problem in any communication system.

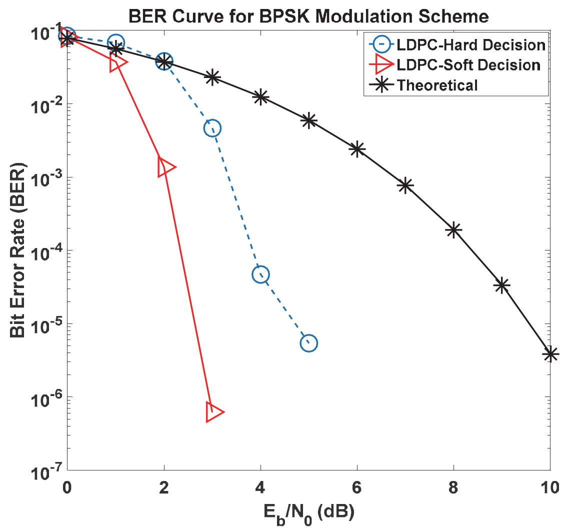

Fig. 4. Comparison of performance between hard decision and soft decision

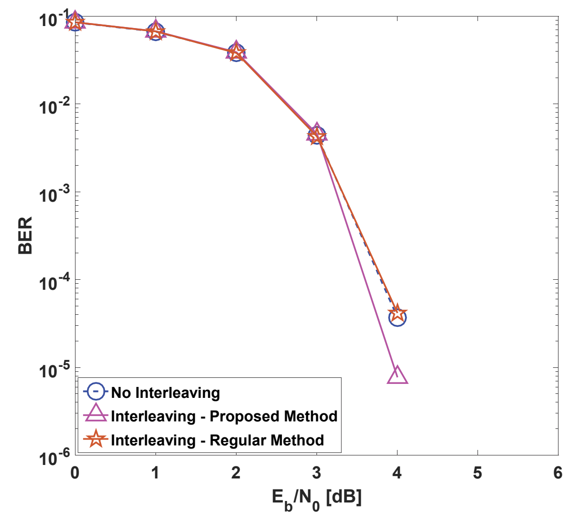

Fig. 5. Performance of interleaved LDPC against white noise

It appears frequently in OSC systems as indicated in experimental results [12], but, it is hard to avoid. To evaluate the performance of LDPC code and interleaving, an LDPC code with the size of 324×648, gap Z = 27, iterations of 30, and BPSK modulation is tested. White noise and burst error are used in simulating the channel environment.

As mentioned above, the soft-decision algorithm can achieve a higher performance than the hard-decision as shown in the Fig. 4. The difference of the performance between the hard decision and the soft decision is about 2 dB. It is shown that LDPC code proves to be effective in both soft decision and hard decision compared to the system without LDPC codes.

However, interleaving with the LDPC code does not show much performance improvement in the white noise environment, as shown in Fig. 5. It is attributed to the fact that the ability of error correction depends on the location of error bits corresponding to the variable nodes which connect to check nodes. In a white noise environment, noise occurs randomly; therefore, a similar performance is achieved. Unlike the white noise case, interleaving brings much improvement against burst error that severely affects system performance. The larger size of the burst error corresponds to the lower capacity of data recovery. However, the burst error will be scattered after interleaving, therefore, it is believed to acquire the high performance. In this simulation, it is assumed that the received bits are zero at the burst error. Comparison between the regular interleaving and the proposed interleaving is shown in Fig. 6. The proposed method has shown a significant difference compared to the regular one and non-interleaving system. The difference is about 10 times. Thus, the method of combining

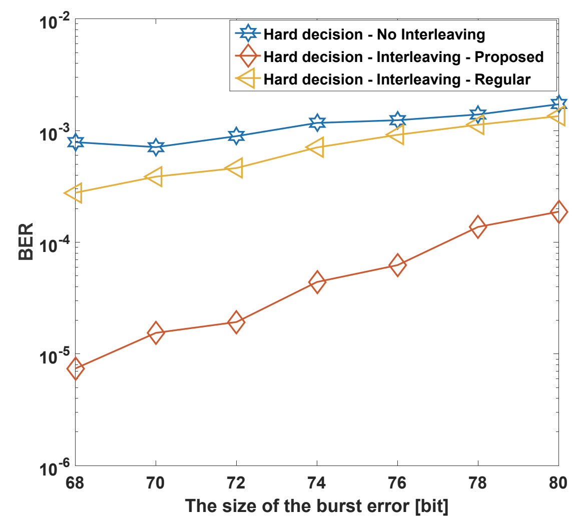

Fig. 6. Performance of the proposed scheme in burst-error environment

LDPC codes and interleaving is considered to be a good alternative for OSC systems.

The system performance will be improved further when a larger size of the LDPC matrix combined with the proposed interleaving is used. Fig. 7 shows the performance of the system when a large size of LDPC matrix 3240×6480, corresponding to the Z = 270 gap is used. As a result, as much as 970 burst error bits can be corrected with the BER of 10^{-4}.

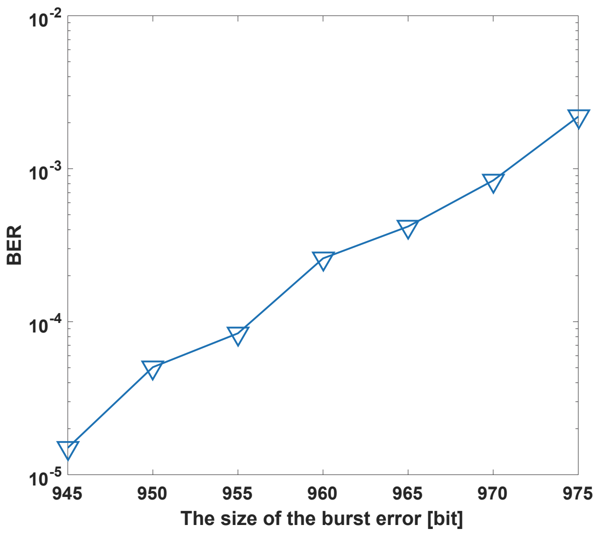

Fig. 7. Performance of interleaved LDPC for different size of burst error

IV. Conclusions

In this paper, LDPC code is used to improve the performance of OSC systems. Soft decision algorithms are proven to achieve better performance than hard decision algorithms. Interleaving method applied for IEEE 802.11 LDPC code is proposed to improve the system performance under burst error condition. Simulation results show that the proposed interleaving scheme can show better performance than the regular one. A burst error of 970 consecutive bits can be corrected by the combination of LDPC code and interleaving.

Acknowledgment

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