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Performance analysis of interleaved LDPC for optical satellite communications

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ABSTRACT

Optical wireless communications 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, an efficient channel coding such as low-density parity check (LDPC) coding is required to satisfy stable transmission. In this paper, fading noise from atmospheric turbulence is reproduced to simulate the satellite channel. Then, this time-varying signal is used to evaluate the performance of the LDPC codes in different channel environments. At the same time, in order to improve the system performance further, an interleaving method in combination with LDPC codes is proposed to overcome the problem of burst error, which frequently occurs in the optical satellite communication systems (OSC). Simulation results show that the block-interleaving scheme can achieve a 5 dB gain compared to the pure LDPC scheme. The processing time is considered to determine the proper size of interleaving blocks suitable for optical satellite communications.

1. Introduction

As communications based on radio frequency have become overloaded in space, Optical Wireless Communications (OWC) has emerged as a new technology due to its outstanding performance, less delay and unlimited bandwidth [1]. Communications based on a laser is considered a very efficient way to transfer signals from the satellite to the earth at high data rate, replacing RF technologies in the near future.

However, OWC in the satellite communications has yet to solve many issues for long distance transmission including atmospheric turbulence and abnormal weather conditions, as shown in Fig. 1. Atmospheric turbulence is a phenomenon of variation in the refractive index of air caused by temperature changes, water vapor, smoke, or other substances. It is the main cause of fading, which will severely impact the light intensity and then degrade the performance of the system. Although the increased laser power can be helpful against this worse channel environment, the power supply of the satellite is always limited. Thus, an efficient coding scheme is one of the solutions to deal with the atmospheric turbulence and improve the performance of the system.

For line-of-sight (LOS) optical systems such as visible light communications (VLC) [2], optical camera communications (OCC) [3,4] and optical satellite communications (OSC), the transmitter and the receiver are in the view of each other. Therefore, any sort of obstacle between them causes the error. Besides, the optical channel will be affected by many obstacles in the outdoor environment like the cloud, bird, rain, snow, etc. In OSC systems, the optical signal is transmitted between the satellite and the ground with a distance of up to thousands of kilometers. Atmospheric turbulence, as well as obstacles in the space, affects the optical transmission channel. The higher the data rate, the larger the number of error bits. As a result, the amount of bits will be lost in a few milliseconds. Assuming that the data rate of satellite communication is 100 Mbps, as much as 1 Mbit data will be lost if the receiver does not see the transmitter for around 10 ms. A burst error size of up to thousand bits is difficult to overcome by using the conventional error correction codes. A few decades ago, Turbo code was known to be the best code to improve the channel performance. In recent years, however, LDPC codes become popular and are used in many applications [5,6]. 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 [5]. Along with Turbo codes, LDPC codes are regarded as the future of Forward Error Correction (FEC) in optical communications. The LDPC codes 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 5G mobile communications [6]. In the satellite communication systems, however, the pure LDPC is not able to guarantee the system stability; therefore, block interleaving is introduced to enhance the performance of the system in the harsh environment.

Optical satellite communication systems have been successfully tested for the satellite communications. Japan Aerospace Exploration

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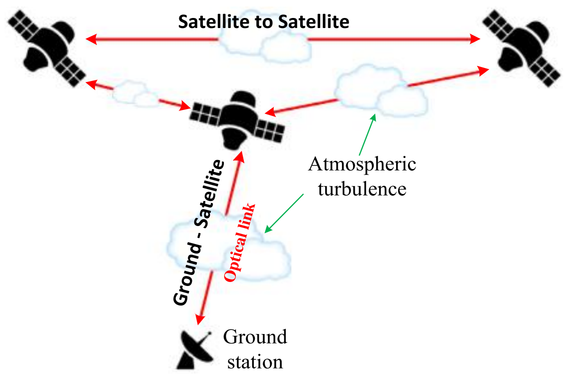

Fig. 1. Channel environment of optical satellite communication systems.

Agency (JAXA) developed the optical inter-orbit communications satellite engineering (OICETS), which has a laser communications terminal called the laser utilizing communications equipment (LUCE). On August 23, 2005, OICETS was successfully launched at an altitude of 610 km [7]. In 2013, NASA established an optical link from lunar orbit to earth. The data rate of downlink and uplink were 40–622 Mbps and 10–20 Mbps, respectively. As a next step, LLRD project will be launched in 2019 with downlink and uplink speeds up to 1.2 Gbps from geo-sync to ground [8]. Also, Facebook is planning to build an optical satellite communication system that will deliver internet access around the world based on drones and satellites.

The primary aim of this paper is to generate the fading environment caused by atmospheric turbulence. Then, the encoded LDPC data, and white noise, as well as burst errors caused by the fading is included in the received signal, which will be processed and decoded to evaluate the LDPC performance for different channel environments. The LDPC code length and the processing time are considered to find out the proper parameters suitable for the system. Block interleaving combined with LDPC code is utilized to improve the performance of the system.

2. Analysis of satellite optical channel and block-interleaved LDPC coding

2.1. Temporal frequency spectrum

There are many power spectrum models of atmospheric turbulence, which is listed in [9]. The power spectrum of atmospheric turbulence is concerned with velocity fluctuations, temperature fluctuations, and index of refraction fluctuations. It can be viewed as a function of the probability of each frequency included in the received signal. According to [10], the temporal power spectrum of atmospheric turbulence can be described as Eq. (1).

$$W_e^2(f) = \frac{0.033C_n^2\tau_r^2D^2}{4V^2}\int_0^\infty \frac{J_1^2\left(\pi D\sqrt{\kappa^2+f^2/V^2}\right)}{\kappa^2+f^2/V^2} \times \frac{\exp\left[-\left(\kappa^2+f^2/V^2\right)/\kappa_m^2\right]}{\left(\kappa^2+f^2/V^2+\kappa_0^2\right)^{11/6}}d\kappa \tag{1}$$

In this equation, the profile model, $C_n^2(h)$, is used to describe the varying strength of optical turbulence as a function of altitude h and wind velocity V; the Hufnagel–Valley (H–V) model [9,10], one of the most widely used schemes, is adopted in this paper. In addition, τ_r is an optical loss, D is the receiver diameter, J_1 is the Bessel function of the first kind, κ is the spatial frequency vector, f is the frequency components in the received signal, $\kappa_m = 5.92/l_0$, $\kappa_0 = 2\pi/L_0$, l_0 is an inner scale and L_0 is an outer scale. It is assumed that the altitudes of satellites and ground stations are constant. Therefore, it is found that the temporal power spectrum is a function of the wind velocity

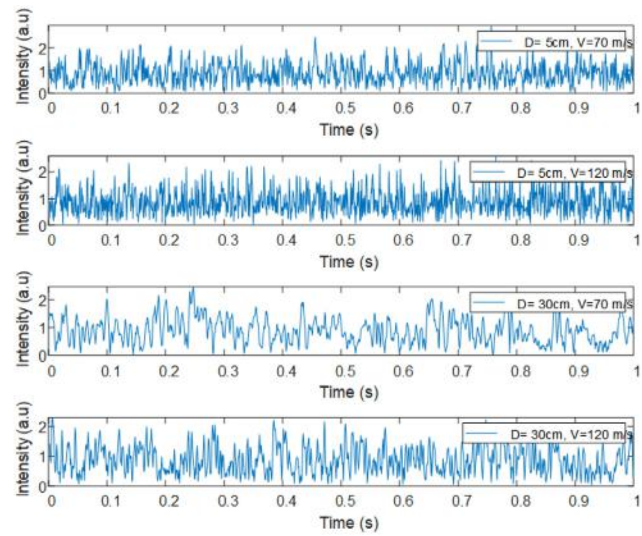

Fig. 2. Time-varying fading signals for different receiver diameters and wind velocities.

(V) and the receiver diameter (D). The power spectral density (PSD) for generating the random time-varying signals can be calculated as in Eq. (2).

$$W_e'(f) = W_e(f) \times \exp\left[j\varphi(f)\right], \tag{2}$$

where $\varphi(f)$ is the random phase in [0, 2π]. Then, the time-varying signals can be generated from the inverse fast Fourier transform as in Eq. (3). The generated signal gives a visualization on the effects of the environment.

$$e(t) = \left|\mathfrak{F}^{-1}\left[W_e'(f)\right]\right| \tag{3}$$

Time-varying fading signals achieved from Eqs. (1) and (3) are shown in Fig. 2, where l_0= 4×10^{-3} m, L_0 = 1.6 m, and C_n^2 = 1.4×10^{-18} m$^{-2/3}$ are assumed at the altitude of 20 km. It can be seen from the figure that the fluctuation frequency increases more with smaller receiver diameter and higher wind velocity.

At the receiver side, the received signal corresponds to the attenuated LDPC encoded data distorted by the fading. In Fig. 3, the frequency spectrum of the received signal is generated by applying the Fast Fourier Transform (FFT) to the encoded LDPC data combined by the fading, and its results are shown in the blue line. It is seen that the dominant frequency-component is within several kHz, much smaller than the signal frequency. It is compared with the PSD generated from Eq. (1), which is indicated in red line named 'Theoretical' in the figure. It is found that the simulated PSD reflecting the atmospheric turbulence follows the trace of theoretical PSD, showing the effectiveness of the simulation process. This 'simulated' signal is used to evaluate the performance of the LDPC codes in the next section. After the addition of encoded LDPC data and the time-varying fading signal, the combined signals are attenuated and decoded. Finally, its performance is evaluated.

2.2. LDPC codes in brief

LDPC codes were originally invented by Gallager in 1960s [11]. Like other block codes, LDPC codes are represented by a parity-check matrix $H(m \times n)$, which has a low density of 1's as in Eq. (4). The generator matrix $G(k \times n)$ is generated from the H matrix, where $k = m - n$ is the length of the information bits. Regular LDPC codes consist of exactly w_c 1's in each column and $w_r = w_c(n/m)$ 1's in each row. The code rate

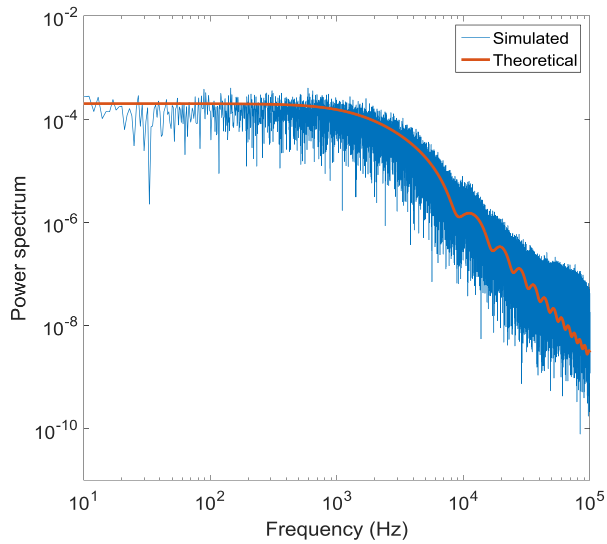

Fig. 3. The frequency spectrum of the simulated signal compared with theoretical PSD.

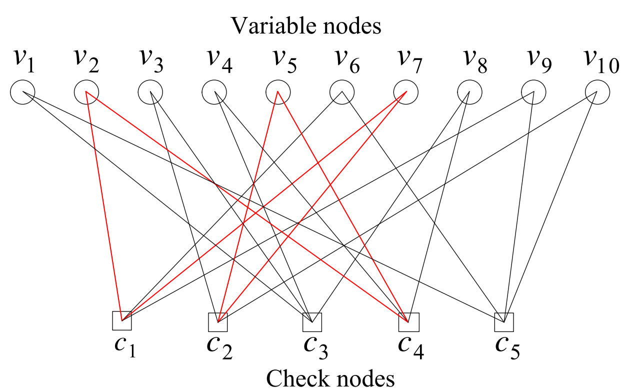

Fig. 4. Tanner graph to represent the parity-check matrix H.

$R = k/n$ is related to these parameters via $R = 1-(w_c/w_r)$. An example of the H matrix (5, 10) with $w_c = 2$ and $w_r = 4$ is shown in Eq. (4).

$$H = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{4}$$

One of the best ways to represent the parity-check matrix H is the Tanner graph as shown in Fig. 4. It is 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 the check node c_j if and only if $H_{ij} = 1$. A cycle length v of Tanner graph is indicated in red lines in Fig. 4 (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 four to achieve high performance.

Since the channel environment of satellite communication systems is very tough, the large size of LDPC codes should be used to achieve high performance. However, the system complexity needs to be considered, which is estimated by the number of operations to accomplish the encoding and the decoding process. To create the codeword, a generator matrix $G = [I\ P]$ must be created by converting the H matrix in the form $[P^T\ I]$ via Gauss–Jordan elimination [12]. However, the P matrix is not sparse, and this method lacks sufficient structure to enable low-complexity encoding. The more efficient method is to convert the H matrix into lower triangular form [13]. This method can reduce the degree of complexity since the matrix is still sparse after the conversion. Hence, it is effective for large matrices.

Decoding of LDPC codes is performed through an iterative process based on a belief algorithm. The decoding process estimates codeword by calculating the probability iteratively, updating and exchanging messages in each edge that connects between variable nodes and check nodes. The decoding process stops when the parity-check condition $r'_x \cdot \mathrm{H}^T = 0$ is satisfied (i.e., r'_x is the received codeword after each iteration), or the number of iterations exceeded the given value. Increasing the number of iterations can improve the system performance, but at the cost of the complexity of the system. There are two types of iterative decoding algorithm: hard decision and soft decision. Soft decision decoder can distinguish the real value between zero and one. Thus, an analog-to-digital converter is required for implementing the soft decision decoder. Although it can achieve high performance, it costs hardware complexity and processing time. On the contrary, hard decision adopts the information of a single bit as '0' or '1'. Therefore, the hard decision is simple and easy to implement. However, the performance of it is lower than that of the soft decision. A large size LDPC can achieve high performance but at the cost of much computation. In this paper, a block-interleaved LDPC is proposed in satellite communications, and its performance is analyzed.

2.3. Burst errors and proposed block-interleaving of the LDPC matrix in 802.11n standard

The burst error is a serious problem of communication systems in harsh environment, where many consecutive bits are lost in a short period. Obstacles in the transmission path and the fading caused by atmospheric turbulence are the main sources of the burst error in the optical satellite communications. The problem of this burst error is that as the number of consecutive error bits are increased, it is not possible to recover the data even with the nominal LDPC coding scheme. An example of the burst error against LDPC coding can be found in Fig. 5, where LDPC encoded signals are transmitted in the fading channel given in Eq. (1). This simulation uses LDPC in IEEE 802.11n standard with size 324 × 648, receiver diameter (D) of 30 cm and wind velocity (V) of 70 m/s. The amplitude of the signal fluctuates a lot due to the fading, and as a result, burst errors happen even after the LDPC decoding. If a short period of time in Fig. 5(a) is magnified, then serious burst errors indicated in red lines are shown as in Fig. 5(b).

Specific 802.11 LDPC matrices are applied to many wireless systems such as Wi-Fi, 5G mobile system and have been shown to be effective. It is expected to work well in the OWC also. The LDPC parity check matrix in 802.11n standards is Quasi-cyclic LDPC matrix (QC-LDPC). It has the minimum Hamming distance with the girth of 6, 8, 10 and 12, which are demonstrated in [14,15]. A parity-check matrix of the QC-LDPC codes has a small size compared to the conventional matrix, and it can be converted to different sizes. Therefore, the QC-LDPC code is very convenient to be used in dynamic systems like satellite communications. Moreover, a QC-LDPC code can save a memory since a small matrix is downloaded to the hardware instead of a thousand bits of parity-check matrix.

LDPC codes have a good performance against Additive White Gaussian Noise (AWGN). However, a small LDPC block cannot overcome a large burst error, while a large one increases the processing time. Therefore, we propose to use a block interleaving for this application. Block interleaving uses multiple small LDPC blocks and combines them. The data of the blocks are not sent in the conventional sequence, but the bits of the interleaved block are sent intermittently in column order. Therefore, if a burst error occurs, the errors are not concentrated in a block, but dispersed across many LPDC blocks. Then, each LDPC block carries only a few errors, and the data recovery can be easier. The structure of the block-interleaved scheme is described in Fig. 6, where z-LDPC blocks are combined to create a large-size block. As the block size becomes larger, the higher performance can be achieved. It requires more delay, however, since the receiver must wait until the whole data of the interleaved block is received.

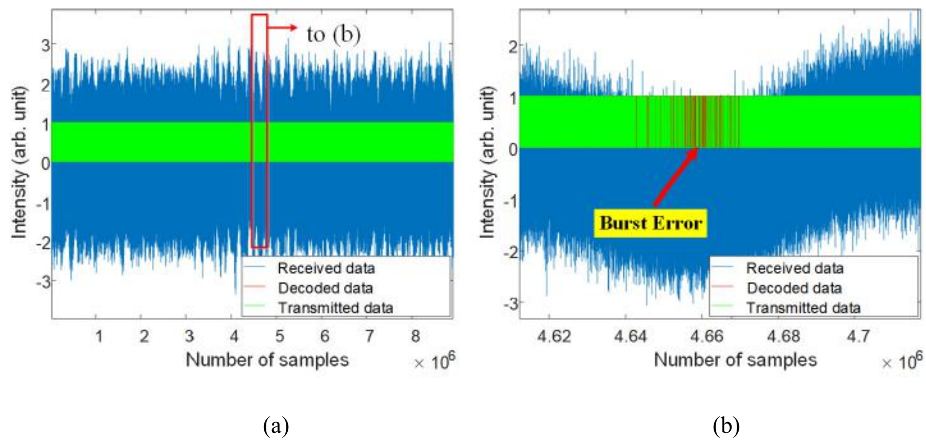

Fig. 5. Burst errors in the fading channel.

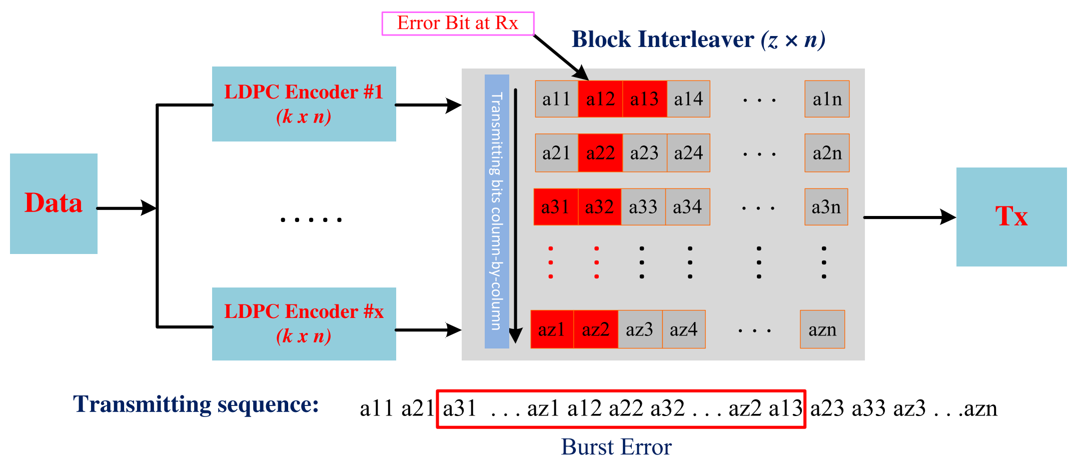

Fig. 6. The scheme of the block-interleaving combined with LDPC coding.

3. Performance analysis of the proposed block-interleaved LDPC coding

In the OSC systems, the channel is influenced a lot by atmospheric turbulence, which degrades the quality of the received signal. In addition, additive white Gaussian noise combined with the burst error degrades the quality of signal more. As a result, the signal is often completely lost or cannot be decoded at a specific time. The burst error appears frequently in the OSC system as indicated in experimental results [16], which is hard to avoid. Therefore, LDPC codes combined with block interleaving is proposed for use in satellite communication systems. In order to evaluate the performance of LDPC code and block-interleaving scheme, an LDPC code of 802.11n standard is adopted, and parameters used in the simulation are listed in Table 1.

Fluctuation with different frequencies is generated for various diameters and wind velocities, which affect the performance of the system directly. Herein, it is assumed that most burst errors come from fading due to atmospheric turbulence, while the SNR is defined as the ratio of signal power to the AWGN. Fig. 7 shows the performance estimation in different channel environments. It is shown that LDPC 648 is very effective when the channel is under only AWGN environment. If there is fading, however, then the LDPC 648 is not so helpful in the performance. Especially, it becomes worse with high wind velocity and small receiver diameter. It is known from this analysis that although LDPC can achieve high performance against AWGN, its performance is degraded severely in the fading channel.

Fig. 8 shows the occurrence of burst errors at different channel environments as 450,000 bits are transmitted. Herein, only burst errors with more than 50 bits are described in bar graphs, while calculated distribution curves for different environments are indicated in three colors. The results show that the occurrence and the size of the burst error are proportional to the wind velocity and inversely proportional to the receiver diameter. The size of the burst error reaches up to 350 bits with the wind velocity of 120 m/s and the receiver diameter of 5 cm.

Performance of block-interleaved LDPC codes is compared with that of the pure LDPC in Fig. 9. It is shown that the performance enhancement with the pure LDPC is not so much, which is attributed to much burst error bits exceeding the capabilities of LDPC 648 as predicted in Fig. 8. Therefore, the employment of pure LDPC is not

Table 1
The environments of the simulation.

Parameter		Value
LDPC codes	Size	324 × 648
	Code rate	0.5
	Iteration	30
Modulation		On–Off Keying
Data rate		1.134 Mbps
Wind velocity		70 m/s
Number of transmitted bits		10^6 bits
Receiver diameter		30 cm
Structure parameter C_n^2		$1.4e^{-18}$ $m^{-2/3}$
Altitude of satellite		20 km
Altitude of ground station		100 m
Inner scale		4 mm
Outer scale		1.6 m

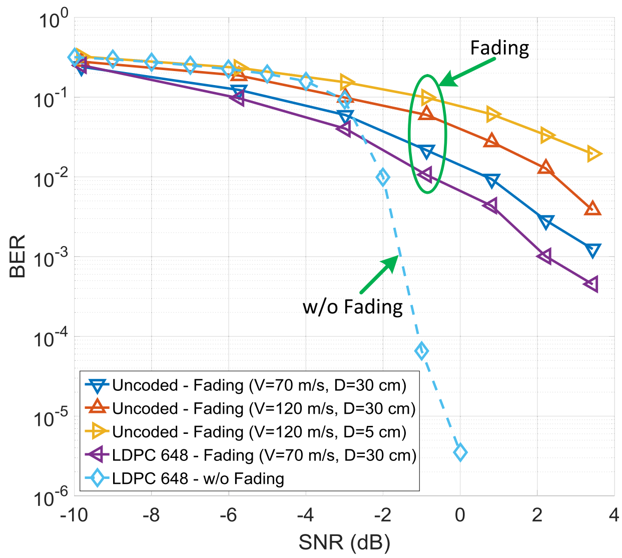

Fig. 7. Performance of the system in different environments.

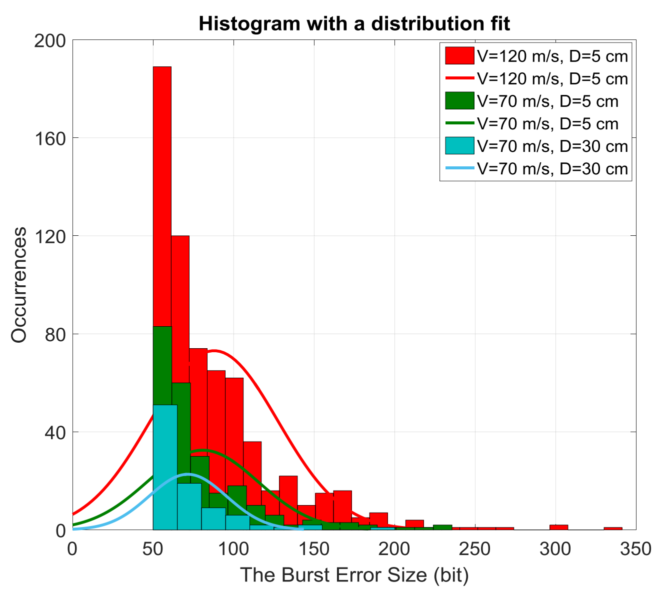

Fig. 8. The occurrence of burst error in the fading channel.

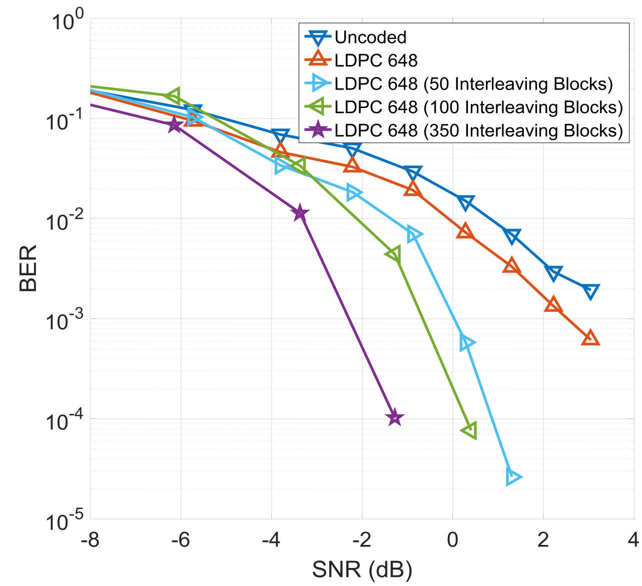

Fig. 9. Performance of block-interleaved LDPC in the fading (V = 70 (m/s), D = 30 (cm)).

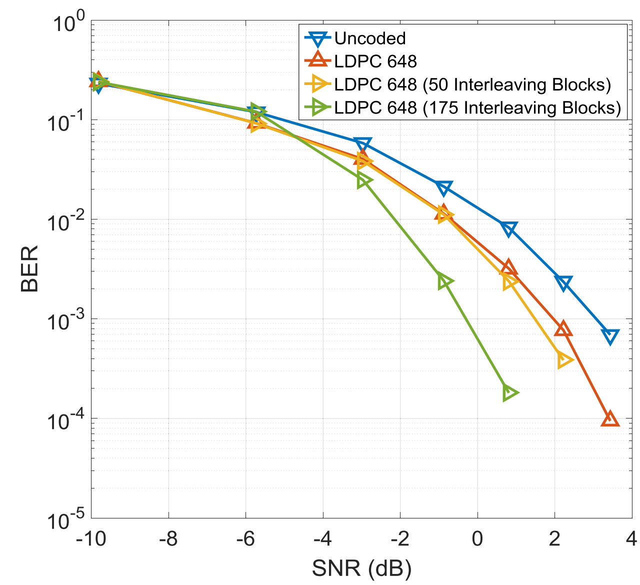

Fig. 10. Performance of LDPC codes for higher data rate.

appropriate in satellite communication systems. In contrast, the block interleaving of LDPC 648 with 50 interleaving-blocks is more effective, showing 2 dB gain at the BER of 10^{-3}. The performance is more improved by increasing the number of interleaving blocks. The LDPC 648 with 350 interleaving blocks achieves 5 dB gain compared to the pure LDPC as shown in Fig. 9.

The effect of the same fading is more serious for higher data rate since the number of burst error bits becomes larger. In Fig. 10, the data rate of 5.67 Mbps, five times higher than the previous simulation is evaluated. This means that the number of burst error bits is increased. As shown in Fig. 10, the performance of the LDPC 648 with 50 interleaving blocks does not show a good performance anymore compared to that of the pure LDPC. Therefore, a larger interleaving-block size is required in this case.

Since LDPC with a small block size cannot overcome large burst errors, it has lower performance compared to the one with a large block size. Therefore, the total block size should be constant for a fair comparison of performance among different LDPC codes. As an example, LDPC 6480 has the same block size as LDPC 648 with 10 interleaving blocks, and the performance of them are close as shown in Fig. 11. It shows that the large size LDPC can improve the performance to the similar amount as the block-interleaved LDPC scheme. However, the processing time need to be considered to choose the appropriate parameters for the system. And the next analysis will prove this view.

Since errors are scattered across many LDPC sub-blocks in interleaved LDPC case, its decoding process requires less iteration in obtaining the specified performance. On the contrary, a large size LDPC code must use more iteration since all errors are concentrated in an LDPC block. Furthermore, its large size parity-check matrix makes the processing time longer. Therefore, the large size LDPC is not preferred due to its processing time. Fig. 12 compares the processing time of these two cases in terms of encoding and decoding when 64,800 bits are processed at Matlab. It is seen that LDPC 6480 requires 22 times and 8 times more computation in encoding and decoding, respectively, compared to LDPC 648 with 10 interleaving blocks at the SNR of 10

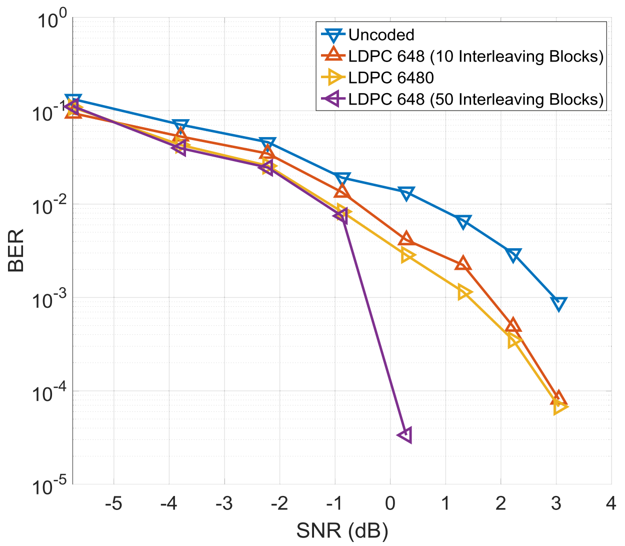

Fig. 11. Comparison of interleaved LDPC with large size LDPC.

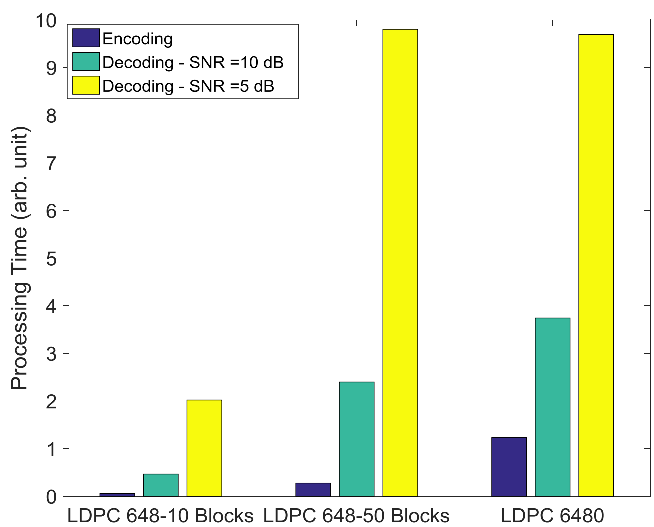

Fig. 12. Comparison of processing time for different LDPC codes.

dB. Furthermore, LDPC 648 with 50 interleaving blocks has the shorter processing time than LDPC 6480 at the SNR of 10 dB even though it has 5 times longer total block length. In practice, moreover, the processing time of interleaved LDPC can be reduced more by decoding the de-interleaved sub-blocks in parallel by using multi-processors. The interleaved LDPC 648 with 50 interleaving blocks achieves 3 dB higher performance than LDPC 6480 as shown in Fig. 11 in short processing time although the block length is five times longer. Although longer block length causes more transmission delay, this amount is negligible compared to the total processing delay. Therefore, it is considered that interleaved LDPC is a good candidate in optical satellite communications. In addition, the number of interleaving blocks should be decided considering the required QoS, system performance, and hardware complexity.

4. Conclusions

In this paper, atmospheric turbulence is generated using the PSD of an optical satellite channel. Time-varying signal is generated from the PSD in different environments. The simulated signal is created by combining the fading signal and encoded LDPC data. The amount of burst error for different environments is shown to demonstrate the impact of the atmospheric turbulence. The performance of LDPC code is evaluated in the OSC system, showing only a 1 dB gain compared to the uncoded scheme. Therefore, LDPC 648 with 350 interleaving-blocks is employed, which leads to a 5 dB gain at the BER of 10^{-4}. The processing time of each LDPC code type is also evaluated. The comparison shows that the block-interleaving scheme requires much shorter processing time compared to the pure LPDC code in both encoding and decoding.

Acknowledgments

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