

Multi-bit random interleaving-LDPC based turbulence effect mitigation in free-space optical communication

YAN-QING HONG*, LU-YAO YANG

School of Information Science and Engineering, Shenyang University of Technology,
Shenyang 110870, China

*Corresponding author: hongy7@sut.edu.cn

The performance of low-density parity-check (LDPC) is severely degraded by the atmospheric turbulence induced consecutive burst errors in free-space optical communication (FSO). Thus, multi-bit random interleaving LDPC (MBI-LDPC) code is proposed to decentralize the consecutive burst errors with computational efficiency. Based on the quasi-stationary characteristics of turbulence channel and stopping set analysis, MBI-LDPC code takes multiple bits as the unit of interleaving. Besides, normalized min-sum algorithm is adopted for the decoding process. Therefore, both burst errors compensation and computational efficiency are achieved. The proposed LDPC code was compared to without LDPC (un-coded), LDPC without interleaving (WOI-LDPC), and single-bit random interleaved LDPC (SBI-LDPC). Simulation results demonstrated that MBI-LDPC code outperformed significantly compared to un-coded, WOI-LDPC, and SBI-LDPC with computational efficiency due to an effective error bits cluster dispersion. Besides, approximately 59.91%, 60.04%, and 59.79% of runtimes were reduced compared to SBI-LDPC scheme in the weak, moderate, and strong turbulence channels.

Keywords: free-space optical communication, LDPC, interleaving.

1. Introduction

Free-space optical communication (FSO) technology is widely adopted in mobile, sensor, and internet of things networks due to an abundant bandwidth resources, high transmission rate, small size, high security, and strong resistance to electromagnetic interference [1]. However, the optical beam is susceptible to atmospheric turbulence induced continuous burst errors, which leads to a significant degradation of FSO link [2]. Therefore, various researches have been carried out to compensate this issue such as adaptive optics, coherent detection, phase modulation, polarization modulation, orbital angular momentum (OAM), and channel coding [3]. Among these solutions, channel coding is the major mitigation technique by achieving channel gains via adding redundant bits.

The performance of Reed–Solomon (RS) code was analyzed for resisting turbulence and correcting burst errors in FSO, and the quantitative relationship between bit-error rate (BER) and signal noise ratio (SNR) was derived [4]. The closed-form expression for the BER of the convolutional code was derived in non-Hermitian orthogonal frequency division multiplexing (OFDM) and polarization diversity FSO system, and an encoding gain of approximately 10 dB was obtained [5]. Turbo codes were studied by combining with convolutional neural network (CNN) to realize adaptive demodulation for the OAM-SK-FSO system under strong turbulence, and the BER was significantly reduced [6]. However, low-density parity-check (LDPC) codes can achieve near-Shannon-limit performance with lower error floors under atmospheric turbulence. Moreover, it offers more flexible code rates and lengths, stronger resistance to burst errors caused by fading and efficient parallel decoding. Thus, LDPC code becomes increasingly popular in FSO links.

LDPC code was studied over Gamma-Gamma turbulence channel, and the capability of turbulence induced fading compensation was verified under OFDM format transmission [7]. The BER performance of LDPC code was analyzed by converting the slow fading into a fast fading channel through spatial multiplexing in FSO channel [8]. Two hard-decision decoding techniques, weighted and implementation efficient reliability ratio weighted bit flipping methods, were proposed in weak, moderate, and strong turbulence channels with the effect of weather attenuation, geometric losses, and misalignment [9]. The link-layer error-control solution was studied by combining of rate compatible LDPC and the incremental redundancy-hybrid automatic repeat request protocol to mitigate cloud coverage, atmospheric turbulence, and pointing errors effects in low-Earth orbit satellite optical communication systems [10]. LDPC coding was integrated into OAM shift-keying modulation, and the communication reliability and pattern recognition capability were refined [11]. However, the capability of error correction was limited by deep fading caused burst error with long duration. Deep learning (DL)-based equalizers was researched in the turbulence channel, and it enables to compensate for the non-linear turbulence-induced distortions which is difficult to describe by the traditional analytical methods [12]. However, the diversity feature of turbulence channel increases the complex network structures and parameter training processes. Therefore, the interleaving mechanism was integrated into LDPC code for the sake of performance improvement.

A bit-interleaved LDPC code was introduced to high-order modulation in additive white Gaussian noise (AWGN) and Rayleigh channels, which improves the coding gains with different block lengths [12]. Mismatched decoding scheme was investigated for bit-interleaved coded modulation to overcome the implementation constraints of clipping and metric approximation [13]. The capacity and BER performance were discussed for Bose Chaudhuri Hocquenghem (BCH) and LDPC coded FSO system, and the expressions of channel capacity were derived for various channel conditions [14]. A single bit deep interleaved LDPC with forward error correction coding (FEC) method was researched for long-distance FSO links, and a 7 km transmission was achieved under weak and strong atmospheric turbulence channels [15]. However, the bit-wise

interleaving increases the computational complexity. Thus, it is essential to study an effective interleaving technique in FSO system.

Multi-bit random interleaving LDPC (MBI-LDPC) is investigated in this work. The unit of interleaving is constructed using multiple bits due to the quasi-stationary characteristics of turbulence channel and the stopping set analysis. Then, normalized min-sum (NMS) algorithm is applied to decode the received signal. The capability of continuous burst error compensation and time consumption were compared between the propose LDPC, without LDPC (un-coded), LDPC without interleaving (WOI-LDPC), and LDPC with SBI-LDPC codes. The comparison results illustrated that the proposed MBI-LDPC code exceed un-coded, WOI-LDPC, and SBI-LDPC schemes significantly with effective error correction and computational efficiency.

2. Operation principle

The optical signal suffers continuous burst fading error issue caused by the atmospheric turbulence effect. Gamma-Gamma distribution model is applied to build the channel model. The probability density function (PDF) of Gamma-Gamma distribution is expressed as

$$f_I(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta}I), \quad I > 0 \quad (1)$$

where α and β represent the effective numbers of small and large-scale eddies in the scattering environment, $\Gamma(\cdot)$ is the Gamma function, and $K_\nu(\cdot)$ is the modified ν -th-order Bessel function [16]. As to the plane wave, α and β are given by

$$\alpha = \left\{ \exp \left[\frac{0.49\sigma_0^2}{(1 + 1.11\sigma_0^{12/5})^{7/6}} \right] - 1 \right\}^{-1} \quad (2)$$

$$\beta = \left\{ \exp \left[\frac{0.51\sigma_0^2}{(1 + 0.69\sigma_0^{12/5})^{7/6}} \right] - 1 \right\}^{-1} \quad (3)$$

where σ_0^2 is the Rytov variance, k is the optical wavenumber, and λ is the wavelength [17]. Thus, weak to strong turbulence channels are accommodated with the corresponding σ_0^2 values of 0.59, 1.19, and 3.98, respectively.

Figure 1 illustrates the block diagram of MBI-LDPC coding and decoding system, which is a stopping-set-aware interleaving strategy structurally integrated with LDPC graph decoding rather than a conventional symbol-wise burst disperser. In the transmitter end, a random bit sequence is encoded into LDPC stream. Then, an interleaving is carried out via interleaver due to the quasi-stationary characteristics of the

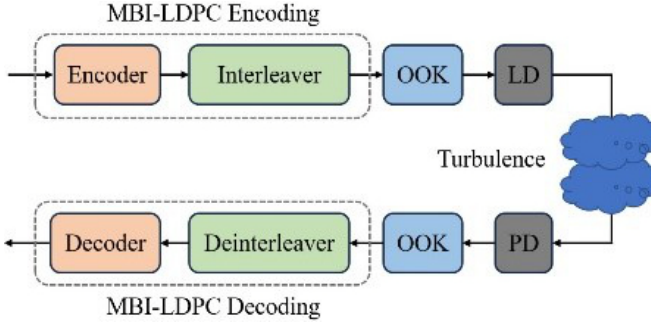


Fig. 1. Block diagram of the MBI-LDPC transmission system.

turbulence channel. The deep fading effect leads to the occurrence of consecutive burst errors. Based on stopping set analysis, the error bits have a high probability of dropping into the small stopping sets within the Tanner graph of LDPC code, and it decreases the capability of decoding convergence. Therefore, the relation between burst errors and stopping sets needs to be considered in LDPC design. The upper bound of the error probability P_e is expressed as

$$P_e \leq \sum_1^{L_b} N_s \frac{L_b}{L} \quad \text{for} \quad L_S \leq L_b \quad (4)$$

where L is the code length, L_b is the average length of burst errors, S is the stopping sets, N_s is the number of stopping sets. L_b is determined by the atmospheric turbulence intensity, L_b and P_e a stronger turbulence gives rise to a larger and values resulting in higher risk of decoding failure [18]. As to N_s , it is determined by the structure of LDPC code, and the value of N_s is needed to be decreased under $L_b < L_S$.

As to the high-order modulation, each symbol carries multiple coded bits. M denotes the modulation order, and the number of coded bits per symbol $m = \log_2(M)$. The burst error length in the symbol domain is denoted as L_b^{sym} and that in the bit domain L_b^{bit} is shown as

$$L_b^{\text{bit}} = L_b^{\text{sym}} \times m \quad (5)$$

In order to have an effective dispersion of burst errors and prevent clustering within vulnerable stopping-set structures in the Tanner graph, the interleaving unit T should satisfy two conditions:

1. T should be an integer multiple of m during permutation, *i.e.*,

$$T = k \times m, \quad k \in \mathbb{Z}^+ \quad (6)$$

2. T should exceed the equivalent burst length in the bit domain, *i.e.*,

$$T \geq L_b^{\text{sym}} \times m \quad (7)$$

Therefore, the optimal T scales proportionally with both the symbol-domain burst length and the number of bits per symbol.

From the channel perspective, T should exceed both L_b and the characteristic size of dominant stopping sets in the Tanner graph, it is approximated as

$$L_b \approx T_c \times R_b \quad (8)$$

where T_c denotes the turbulence coherence time, and R_b is the bit rate. Since T_c is related to atmospheric turbulence intensity (*e.g.*, Rytov variance), the burst length can be estimated from channel state information. Therefore, the guideline for selecting T can be expressed as

$$T \geq \max(L_b, S_{\min}) \quad (9)$$

where $S_{\min}$ represents the small stopping-set size of the LDPC code. This adaptive selection mechanism can be implemented in real time by first estimating the turbulence strength (*e.g.*, via received signal variance or Rytov variance estimation), and then approximating L_b and selecting T from a predefined lookup table. Since the adjustment process only changes the permutation unit size without modifying the LDPC decoding structure or iteration process, it introduces negligible complexity. Besides, it does not change the intrinsic number of stopping sets N_s in the Tanner graph. Instead, it reduces the probability that burst errors fully activate small stopping sets, which effectively decreases the contribution of N_s to the error floor. As to SBI, the burst-error segments are mapped onto vulnerable local graph structures randomly, which may result in the clusters of consecutive errors mapped into variable nodes belonging to the same small stopping set. The error probability P_{SBI} is approximated as

$$P_{\text{SBI}}(s) \approx \left(\frac{L_b}{L} \right)^s \quad (10)$$

With regard to the MBI, the error probability P_{MBI} is given by

$$P_{\text{MBI}}(s) \approx \left(\frac{L_b}{L} \right)^s \times \eta(T) \quad (11)$$

where $\eta(T) < 1$ represents the structural dispersion factor introduced by block-level grouping. The factor $\eta(T)$ decreases as T is properly selected to match the burst coherence length, because burst errors are forced to occupy different block indices after permutation, reducing the likelihood that all variable nodes of S are simultaneously covered. Therefore, although the inherent number of stopping sets N_s determined by the parity-check matrix remains unchanged, the effective activation probability of harmful stopping sets is reduced due to $P_{\text{MBI}} < P_{\text{SBI}}$.

Figure 2 depicts the block diagram of the multi-bit interleaving scheme. Based on the criteria from formula (4), the proposed MBI-LDPC is designed to actively dis-

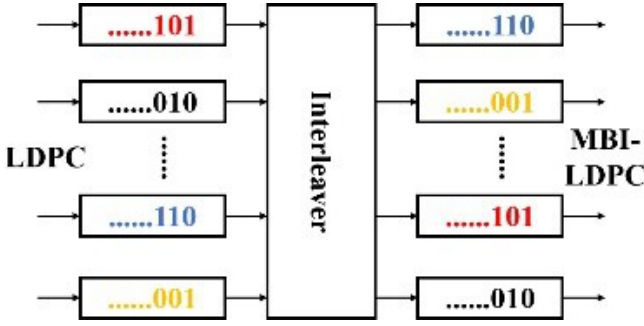


Fig. 2. Block diagram of the multi-bit interleaving scheme.

perse error bit clusters through a localized bit permutation operation, so as to mitigate the adverse impact of turbulence-induced burst errors on LDPC decoding. LDPC bit sequence $x = [x_1, \dots, x_L]$ is divided into blocks with $T = L/Q$ bits, where Q is the number of blocks. The divided blocks are initialized into $x^{(1)} = [x_1, \dots, x_T]$, ..., $x^{(Q)} = [x_{(Q-1)T}, \dots, x_T]$. Then, a permutation vector $\pi = [\pi(1), \dots, \pi(Q)]$ is introduced to map the i -th group of bits into $\pi(i)$, and the interleaved bit sequence $y = [x^{\pi^{-1}(1)}, \dots, x^{\pi^{-1}(Q)}]$ is constructed successfully. Then, MBI-LDPC is modulated into on-off keying (OOK) format and transmitted into the turbulence channel. As to the received OOK signal, the inverse permutation π^{-1} is adopted to conduct the deinterleaving operation, and then, NMS algorithm is applied to distinguish the received bit sequence. Besides, it can alleviate the phenomenon of error bit concentration on the certain check node comparing with single-bit interleaving method. Furthermore, the multiple bits formed unit of interleaving reduces the computational complexity of interleaving as well. Therefore, the atmospheric turbulence caused deep fading effect is effectively mitigated by the proposed MBI-LDPC scheme with computational efficiency in FSO link.

3. Simulation and results

According to IEEE 802.11n standard, the regular LDPC codes were selected with the code length of 648, 1296, and 1944, and code rate R of $1/2$, $2/3$, $3/4$, and $5/6$ in simulation for the sake of evaluating the performance of the proposed MBI-LDPC transmission. The normalization factor Z of 0.7 and iteration of 5 were configured into the NMS algorithm.

Figure 3 shows the BER performance of MBI-LDPC code with different code lengths of 648, 1296, 1944 and code rates of $1/2$, $2/3$, $3/4$, $5/6$. Weak turbulence channel with σ_0^2 value of 0.59 was accommodated, and the length of interleaved block T was set into 30 bits. Since a long code length provides a large statistical coding gain, and the low code rate supports much more quantities of redundant bits. MBI-LDPC with $k = 1944$ and $R = 1/2$ exhibited the best BER performance under various SNRs. Therefore, MBI-LDPC with $k = 1944$ and $R = 1/2$ was applied in the subsequent discussion.

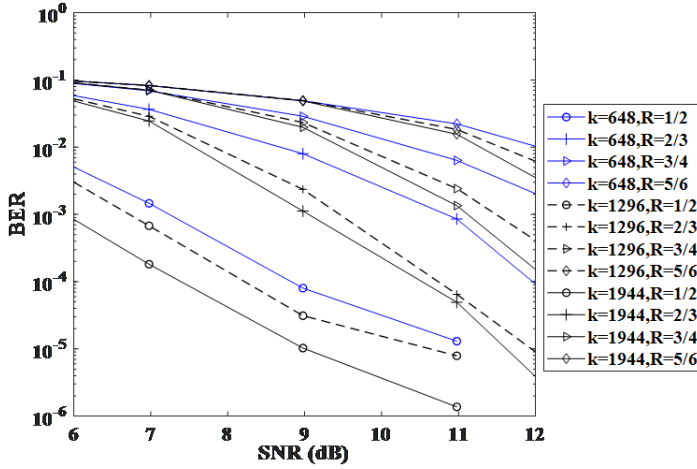


Fig. 3. BER performance of MBI-LDPC with different code lengths and rates.

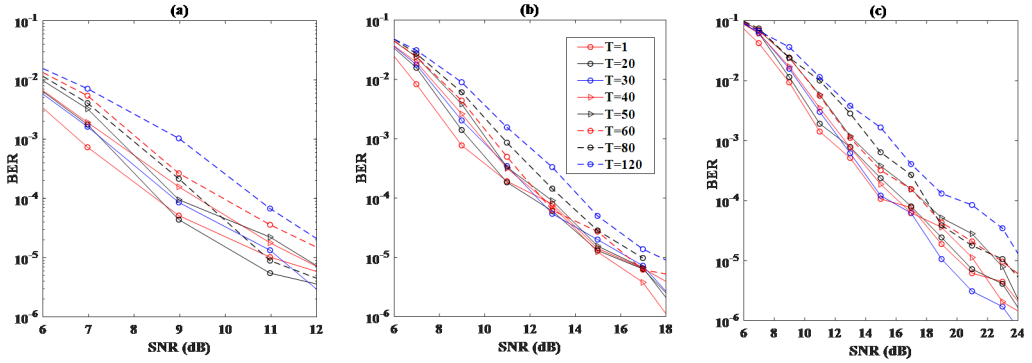


Fig. 4. BER performance of MBI-LDPC code with various T values under σ_0^2 of (a) 0.59, (b) 1.19, and (c) 3.98.

Figure 4 illustrates the BER performance of MBI-LDPC code with various numbers of bits in the interleaved blocks. MBI-LDPC was degraded into SBI-LDPC in the case of $T = 1$. With respect to weak turbulence channel σ_0^2 with of 0.59, MBI-LDPC with $T = 20$ outperformed MBI-LDPC with $T = 1, 30, 40, 50, 60, 80$, and 120. As to moderate and strong turbulence channels with σ_0^2 of 1.19 and 3.98, the best BER values were achieved by MBI-LDPC with $T = 40$ and $T = 30$, respectively. The optimal T does not increase linearly with turbulence intensity. This is because different turbulence channels have different length of burst error bits due to the random fading character of turbulence effect. Thus, various T values were required to realize a high level of error bits dispersion to avoid the risk of stopping set coverage.

The proposed MBI-LDPC was compared to un-coded, WOI-LDPC, and SBI-LDPC under various turbulence channels in Fig. 5. MBI-LDPC with $k = 1944$, $R = 1/2$, and

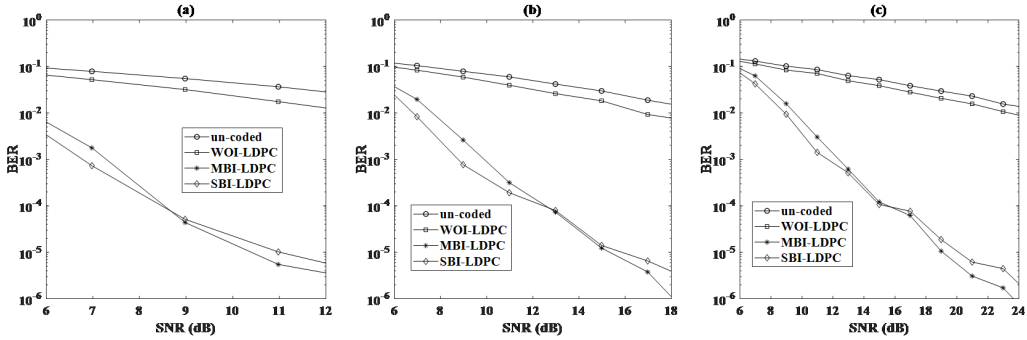


Fig. 5. Performance comparison between MBI-LDPC, un-coded, WOI-LDPC, and SBI-LDPC under σ_0^2 of (a) 0.59, (b) 1.19, and (c) 3.98.

$T = 20, 40, 30$ were adopted in channel with σ_0^2 of 0.59, 1.19, and 3.98. BERs were improved slightly by the application of LDPC without bit interleaving compared to the method without LDPC. It is obvious that BERs were enhanced significantly by the adoption of interleaving mechanism, and MBI-LDPC exceeds SBI-LDPC in the high SNR region. In the low SNR region, the performance is mainly dominated by random noise, thus the interleaving structure has limited influence on decoding behavior. However, with the increases of SNR values, the noise-induced errors decreased and the burst-error pattern caused by turbulence effect becomes a dominant factor. Thus, the proposed interleaving method can effectively disperse error clusters, thereby reducing the probability of stopping-set concentration and improving decoding convergence. Besides, the computational efficiency of MBI-LDPC was evaluated by assessing the runtime of interleaving and total processing as shown in Table 1 and 2. Approximately 52.75%, 49.77%, and 51.45% of interleaving runtime were reduced by MBI-LDPC compared to SBI-LDPC scheme in the weak, moderate, and strong turbulence channels due to the multiple bits based interleaving. Besides, around 59.91%, 60.04%, and 59.79% of total

Table 1. Runtime of interleaving.

σ_0^2	MBI-LDPC	SBI-LDPC
0.59	0.0833 s	0.1763 s
1.19	0.0862 s	0.1716 s
3.98	0.0856 s	0.1763 s

Table 2. Runtime of total processing.

σ_0^2	MBI-LDPC	SBI-LDPC
0.59	1.0161 s	2.5343 s
1.19	1.0235 s	2.5614 s
3.98	1.0382 s	2.5817 s

processing were reduced by MBI-LDPC as well. Therefore, both BER performance and computational efficiency were realized by the proposed MBI-LDPC scheme.

4. Conclusions

In summary, MBI-LDPC was proposed to address the consecutive burst errors in FSO. MBI-LDPC scheme was designed according to the quasi-stationary characteristics of turbulence channel and stopping set analysis. MBI-LDPC code was evaluated towards the ability of error correction and computational efficiency under the optimization of block length, code length, and code rate. Besides, MBI-LDPC was compared to un-coded, WOI-LDPC, and SBI-LDPC in simulation. Simulation results illustrated that both error correction and computational efficiency were improved dramatically by the proposed MBI-LDPC code. Thus, it provides an alternative way to enhance the performance of FSO links.

Funding

This work was supported by the Joint Program of Science and Technology Plan of Liaoning Province (Natural Science Foundation General Program) under Grant 2025-MSLH-527 and Department of Education of Liaoning Province under Grant JYTMS20231214.

References

- [1] ZUO Y., YUE M.Y., YANG H.Y., WU L.T., YUAN X.J., *Integrating communication, sensing and computing in satellite Internet of Things: Challenges and opportunities*, IEEE Wireless Communications, **31**(3), 2024: 332–338. <https://doi.org/10.1109/MWC.019.2200574>
- [2] KHALIGHI M.A., UYSAL M., *Survey on free-space optical communication: A communication theory perspective*, IEEE Communications Surveys & Tutorials, **16**(4), 2014: 2231–2258. <https://doi.org/10.1109/COMST.2014.2329501>
- [3] ALTAKHAINEH A., ALSARAYEH S., ALRAWASHDEH R., ALEID A., ALSHARARI F., ALODAT R., *Outdoor free space optical systems: motivations, challenges, contributions in environmental conditions, and future directions—A systematic survey*, IEEE Access, **13**, 2025: 49121–49161. <https://doi.org/10.1109/ACCESS.2025.3549776>
- [4] HELAL M., KANDOUCCI C., BOUZIANI M., *Mitigating atmospheric turbulence in FSO communications using Reed-Solomon coding: A performance analysis*, Opto-Electronics Review, **33**(4), 2025: e157331. <https://doi.org/10.24425/opelre.2025.157331>
- [5] TIAN Q., LI Z., HU K., ZHU L., PAN X., ZHANG Q., WANG Y., TIAN F., YIN X., XIN X., *Turbo-coded 16-ary OAM shift keying FSO communication system combining the CNN-based adaptive demodulator*, Optics Express, **26**(21), 2018, 27849–27864. <https://doi.org/10.1364/OE.26.027849>
- [6] QUAIUM A., BARUA B., SHARIFUL ISLAM M., MORSHED M., *A closed-form solution of BER for a convolutional coded non-Hermitian OFDM FSO system with polarization diversity*, Journal of Optical Communications, **46**(4), 2024: 945–955. <https://doi.org/10.1515/joc-2024-0190>
- [7] DJORDJEVIC I.B., VASIC B., NEIFELD M., *LDPC-coded OFDM for optical communication systems with direct detection*, IEEE Journal of Selected Topics in Quantum Electronics, **13**(5), 2007: 1446–1451. <https://doi.org/10.1109/JSTQE.2007.901893>
- [8] SONALI, DIXIT A., JAIN V.K., *Analysis of LDPC codes in FSO communication system under fast fading channel conditions*, IEEE Open Journal of the Communications Society, **2**, 2021: 1663–1673. <https://doi.org/10.1109/OJCOMS.2021.3095758>

- [9] YOUSSEF A.A., ABAZA M., ALATAWI A.S., *LDPC decoding techniques for free-space optical communications*, IEEE Access, **9**, 2021: 133510–133519. <https://doi.org/10.1109/ACCESS.2021.3116081>
- [10] NGUYEN C.T., LE H.D., NGUYEN C.T., PHAM A.T., *Toward practical HARQ-based RC-LDPC design for optical satellite-assisted vehicular networks*, IEEE Transactions on Aerospace and Electronic Systems, **60**(6), 2024: 8619–8634. <https://doi.org/10.1109/TAES.2024.3434768>
- [11] LI Z.K., SHANG T., LIU X.C., QIAN P.H., ZHANG Y.L., *LDPC-coded OAM shift-keying FSO communication system with dual-pattern CNN demodulator*, Physical Communication, **68**, 2025: 102567. <https://doi.org/10.1016/j.phycom.2024.102567>
- [12] JIN D.R., CHEN Y., LU Y., CHEN J.Z., WANG P., LIU Z.C., GUO S., BAI X.Z., *Neutralizing the impact of atmospheric turbulence on complex scene imaging via deep learning*, Nature Machine Intelligence, **3**, 2021: 876–884. <https://doi.org/10.1038/s42256-021-00392-1>
- [13] NOWAK S., KAYS R., *An interleaving scheme for efficient binary LDPC coded higher-order modulation*, [In] 2010 International ITG Conference on Source and Channel Coding (SCC), Siegen, Germany, 2010: 1–6.
- [14] NGUYEN T.T., LAMPE L., *Bit-interleaved coded modulation with mismatched decoding metrics*, IEEE Transactions on Communications, **59**(2), 2011: 437–447. <https://doi.org/10.1109/TCOMM.2011.121410.100281>
- [15] SONALI, GUPTA N., DIXIT A., JAIN V.K., *Capacity and BER analysis of BCH and LDPC coded FSO communication system for different channel conditions*, Optical and Quantum Electronics, **53**, 2021: 267. <https://doi.org/10.1007/s11082-021-02949-1>
- [16] AL-IMRAN, CHOWDHURY M.Z., BIN MOFIDUL R., JANG Y.M., *Machine learning and deep learning in fso communication: A comprehensive survey*, ICT Express, **11**(6), 2025: 1026–1046. <https://doi.org/10.1016/j.icte.2025.10.007>
- [17] WU W., XIE J., BAI L., *Improved equivalent optical turbulence method for anisotropic compressible and atmospheric turbulence under different beam transmission distances*, Scientific Reports, **15**, 2025: 3394. <https://doi.org/10.1038/s41598-025-87849-0>
- [18] BOLUDA-RUIZ R., GARCIA-ZAMBRANA A., CASTILLO-VAZQUEZ B., CASTILLO-VAZQUEZ C., *Ergodic capacity analysis for DF strategies in cooperative FSO systems*, Optics Express, **23**(17), 2015: 21565–21584. <https://doi.org/10.1364/OE.23.021565>
- [19] NASERI S., *Error Floor Analysis of Quasi-Cyclic LDPC and Spatially Coupled-LDPC Codes and Construction of Codes with Low Error Floor*, Ph.D. Thesis, Carleton University, Canada, 2021. <https://doi.org/10.22215/etd/2021-14438>

*Received November 25, 2025
in revised form February 13, 2026*