Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2014, P-17, Kobe, Japan, May 7-9 (2014)

Comparative Study on Low-Rate Forward Error Correction Codes in Downlink Satellite-to-Ground Laser Communications

Hiroaki Inoue†, Eiji Okamoto†, Yozo Shoji‡, Yoshihisa Takayama‡, and Morio Toyoshima‡
†Department of Computer Science and Engineering, Graduate School of Engineering,
Nagoya Institute of Technology
Gokiso-cho, Syowa-ku, Nagoya, 466-8555 Japan
‡Space Communication Systems Laboratory, Wireless Network Research Institute,
National Institute of Information and Communications Technology.
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795
E-mail: †okamoto@nitech.ac.jp

Abstract— **In high-speed satellite-to-ground laser communications, it has been shown that the Markov-based erasure channel model is well suited for the downlink experiment results. In that model, since the average erasure rate is relatively high, a low-rate error correction code is needed. In this paper, we focus on the application of low rate systematic Luby transform (SLT) code and show that the performance of SLT code is better than low-density generator matrix (LDGM) code in the downlink satellite-to-ground laser channel when using a short interleaver.**

Keywords- satellite-to-ground laser communications; LT codes; LDGM codes; forward error correction; interleaver.

I. INTRODUCTION

Free space optical communication using hundred THz frequency band is free from the radio regulations and enables very high-capacity transmission. It may solve the current shortage of radio wireless frequency bands and is expected to be developed. National institute of information and communications technology (NICT) had satellite laser communication experiments using the test satellite named Optical Inter-orbit Communications Engineering Test Satellite (OICETS) to exploit the free space optical communications. In the experiments it has been confirmed that a burst error occurs in transmission because of the periodic received optical power degradation caused by air scintillation [1]. From this results, a channel model of downlink satellite-to-ground laser link has been proposed [2]. Japan Aerospace eXploration Agency (JAXA) plans to launch the Space Optical Communications Research Advanced Technology Satellite (SOCRATES) which is share-ride of ALOS-2 [3]. In SOCRATES a small optical transponder named Small Optical Transponder for micro-satellite (SOTA) is equipped as the optical satellite station and various laser communication experiments are planned by NICT between NICT's ground station and SOTA [4,5].

In [2] the downlink laser channel is modeled as the burst erasure channel in which the received symbol is treated as correct or erased by using a relatively high threshold of receive power. Thus, channel coding is indispensable for this channel. The channel coding consists of Automatic Repeat-reQuest (ARQ) and forward error correction (FEC), and the integrated use of both methods is most effective. However, the altitude of OICETS and SOCRATES are 610 and 630 km, respectively, and the communication time with such a low-earth orbit satellite is a few ten minutes which is a very limited span. In that case, the one-way downlink transmission with strong FEC will be a good scheme to enhance the throughput because ARQ needs two-way communication and double transmission delay time. Therefore, we focus on the FEC utilization for the satellite-to-ground link, and exploit the efficient FEC for this channel.

We have proposed a use of low-density generator matrix (LDGM) code [6], a type of low-density parity check (LDPC) code, with an interleaver for the satellite laser downlink channel as a strong FEC code, and have shown the good performance through computer simulations [7]. From this results the LDGM code is adopted as FEC code in SOTA and the transmission experiments are planned [8,9]. However, when the burst length is increased because of the burst erasure in fast transmission in the optical channel, a long interleaver is needed to change burst erasure into random erasure and to make the channel code effectively works. This results in the increase of memory size which is undesirable for the satellite transmitter and receiver such as SOTA. In addition to that, the average bit erasure rate of downlink laser channel is around 50 to 60% and the low rate code may be required. The low-rate LDGM code for those channels is sometimes not good in terms of error correction ability because the density of parity check matrix becomes higher. However, low-rate codes

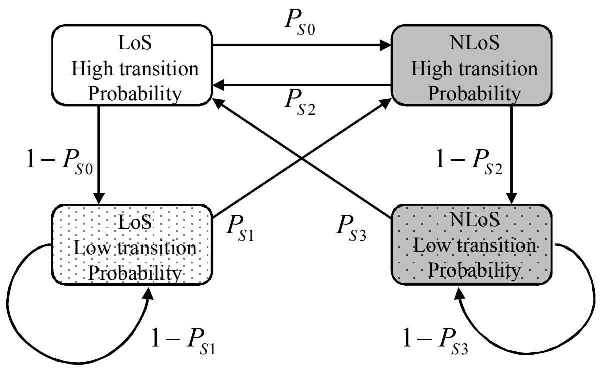

Fig. 1 Four state Markov model of downlink satellite-to-ground channel.

having good performance in such erasure channel is not fully considered. Therefore, in this study, we propose a use of lower rate Luby transform (LT) code [10], which is a type of LDPC code, and systematic LT (SLT) code [11], which is a systematic type code of LT, with a compact interleaver to obtain good error correction performance with small memory size in the satellite laser downlink channel.

In the following, the satellite laser downlink channel and the configuration of interleaver proposed in [2] is briefly reviewed in Section II. LDGM, LT, and SLT codes are introduced in Sections III and IV, respectively. Numerical results of error correction performance comparison are shown in Section V, and the conclusion is drawn in Section VI.

II. ERASURE CHANNEL MODEL OF SATELLITE LASER DOWNLINK AND INTERLEAVER

Fig. 1 shows the four-state Markov model of downlink satellite-to-ground channel derived by OICETS experiment results in which the variables P_{S0} to P_{S3} are the transition probabilities. In this model, there are two groups of line-of-sight (LoS) and non-line-of-sight (NLoS). An erasure-free transmission is obtained in LoS states and all erasure occurs in NLoS states. Two LoS types of short and long period exist which are unstable and stable LoS condition, respectively. Two NLoS types are the same as LoS states. This model well coincides the probability density function of burst LoS/NLoS periods on optical received power in the OICETS experimental results. The erasure rate becomes about 60 % on average in this channel. The channel coherent time (transition period) depends on the receiver clock time and 0.05 ms is used in OICETS experiments [2]. To distribute the burst erasure and make it a random erasure for the enhancement of error correction ability, the interleaver is indispensable in the satellite laser downlink. In this study, the non-binary code is adopted for higher rate transmission and the symbol interleaver is used. Fig. 2 shows the configuration of the interleaver. The interleaver size is longer than the code length

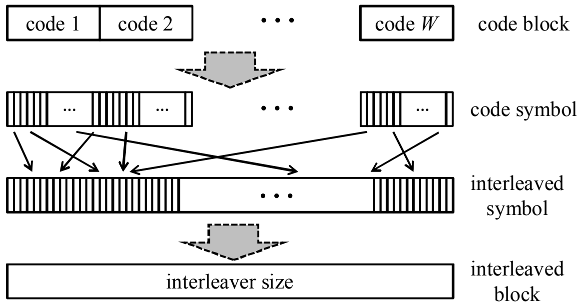

Fig. 2 Configuration of interleaver.

to expand the effect of averaging burst erasure. Using W codewords the interleaving is conducted. When W is increased more equivalent random erasure channel is obtained but also the longer memory size is required, and the longer waiting time for W codeword reception is needed, that causes the delay time in decoding. Hence, the optimal interleaving size exists.

III. LOW DENSITY GENERATOR MATRIX CODE

LDPC code has strong error correction ability and there are two types of the LDPC code, regular and irregular. In regular LDPC codes, the weight of each row and the weight of each column in the check matrix are the same, respectively, and otherwise that code is an irregular LDPC. In general, the generation of the check matrix of regular LDPC is easier, while the error correction performance of irregular LDPC is often better than that of regular LDPC. In LT and SLT codes described in Section IV, these weights are randomly determined by a probability distribution so that they are categorized as the irregular LDPC. The LDGM and SLT codes are systematic codes and if the information symbols are not erased, the decoding can be immediately finished by extracting that information symbol part, while non-systematic codes such as LT code always need decoding calculation.

LDGM is a kind of LDPC code and both encoding and decoding can be done by the check matrix. The check matrix of LDGM code $\mathbf{H}_{\mathbf{LDGM}}$ is given by

$$\mathbf{H}_{\mathbf{LDGM}} = [\mathbf{H}_{\mathrm{S}} \,|\, \mathbf{H}_{\mathrm{P}}] \tag{1}$$

where $\mathbf{H}_{\mathbf{S}}$ is the random regular submatrix whose row and column weights are w_j and w_k, respectively, and $\mathbf{H}_{\mathbf{P}}$ is the parity submatrix which is unit-like matrix and two diagonal elements are 1. The LDGM code with this $\mathbf{H}_{\mathbf{P}}$ is called LDGM Staircase code and its error correction ability becomes higher than normal LDGM code [6]. In the LDGM Staircase code used in this study, the code length N is determined by the information length K as

$$N = \left(1 + \frac{w_j}{w_k}\right) K \tag{2}$$

Let the information symbols as $\mathbf{m}=\{m_1, \ldots, m_K\}$ and codeword as $\mathbf{c}=\{c_1, \ldots, c_N\}$, where m_k and c_n $(1 \le k \le K, 1 \le n \le N)$ is a finite number on Galois field $G(2^q)$, and q is a natural number. Because the LDGM is a systematic code, $\mathbf{c}$ is given by

$$\mathbf{c}=\{c_1, \ldots, c_N\}=\{m_1, \cdots, m_K, p_1\cdots, p_{N-K}\} \quad (3)$$

and the parity symbols $p_1, \ldots, p_{N-K}$ are calculated with j-th row and k-th column element $h_{\mathrm{LDGM}\,jk}$ of $\mathbf{H}_{\mathbf{LDGM}}$ by

$$p_j = \sum_{k=1}^{K+(j-1)} c_k \cdot h_{\mathrm{LDGM}\,jk} \quad (4)$$

Note that because $\mathbf{H}_{\mathbf{P}}$ is a double diagonal unit matrix, p_k can be sequentially calculated from p_1 to p_{N-K} using p_{k-1}. In decoding, the error correction, that is the recovery from erasure, is conducted by iterative decoding algorithm or Gaussian Elimination (GE) algorithm. In the iterative decoding, one erasure in (4) equation is searched and the recovered by summation of other symbols. This recovery operation is iterated until all erasure is recovered or all of one erasure in one equation are addressed and more than two erasures are left. Because the decoding algorithm of LT and SLT codes is similar to the iterative decoding, the iterative decoding is considered for comparison in this study.

IV. Luby Transform and Systematic LT codes

LT code is a family of LDPC codes. The encoding of LT can be processed semi-permanently and the decoding can be started at the length of information symbol reception. Hence, LT codes are utilized for multicast distribution [11]. The encoding is conducted by summation of randomly selected information symbols with the probability distribution of degree (the number of symbols) and symbol selection. When K is the number of information symbols and N is the number of codeword symbols, the encoding process is described as follows.

(e1). Using a specific probability distribution function one integer between 1 and K is randomly generated as degree.

(e2). The information symbols are randomly selected in which the number of symbols is the degree integer generated at (e1), and the summation of those symbols and output as the codeword symbol.

(e3). (e1) and (e2) are iterated N times and N symbols are output as a codeword.

There are some functions for the degree distribution and Robust Soliton distribution (RSD) [10] is a popular one, which is used in this study. The detailed algorithm of (e1) to (e3) is described as follows.

Let information symbols as $\mathbf{m}=\{m_1, \ldots, m_K\}$ and codeword as $\mathbf{c}=\{c_1, \ldots, c_N\}$ where m_k and c_n $(1 \le k \le K, 1 \le n \le N)$ are the elements on GF (2^q). When the generated degree of each symbols is denoted as $d_1, \ldots, d_N$ and the connection between symbols is denoted as $\mathbf{H}=\{\mathbf{h}_1, \ldots, \mathbf{h}_N\}$, $\mathbf{h}_l=\{h_{l1}, \ldots, h_{ld_l}\}^T$ and $1 \le l \le N$, the l-th encoded symbol is calculated by

$$c_l = \sum_{j=1}^{d_l} m_{h_{lj}} \quad (5)$$

where $1 \le d_l \le K$ and ^{T} describes the transpose. In particular, when p=1, Eq. (5) can be calculated by eXclusive OR (XOR). Hereafter, the degree and the connection are referred to as 'prior-information' as a whole.

The decoding of LT codes is sequentially conducted using the degree information of each symbol as follows. Here, it is assumed that the prior-information is shared by the transmitter and the receiver by some additional information such as random seed sharing.

(d1). The received symbol with degree=1 is searched.

(d2). If it is found, the received symbol is immediately decoded as the information symbol since degree=1.

(d3). Using the decoded symbol, all connected received symbols are subtracted by the decoded symbol. Then the degree of those connected symbols is decremented and this connection is cut off.

(d4). (d1) to (d3) are iterated until all information symbols are decoded or all degree=1 are consumed. If remained undecoded information symbol exists, wait another reception or stop the decoding algorithm.

Since this algorithm is iteratively executed, it is called iterative decoding. (d1) can be started at the time of K symbol reception and thus, LT codes enable the sequential reception and decoding.

In SLT code the codeword is composed from the information symbols as well as (3) and the parity symbols p_1 to p_{N-K} is calculated in the same manner to LT code. The decoding algorithm is also the same as the iterative algorithm of LT code. However, when the RSD of LT code is directly used to SLT code, sometimes the parity symbol may be the information symbol (degree=1) and the coding effect is lowered. To avoid this the modified probability distribution based on RSD is considered [13,14] and the Improved RSD (IRSD) [13] is used here. In IRSD the average degree is the same as RSD but degree=1 is not generated to avoid that case.

V. Numerical results

We compare the packet error rate (PER) performances of LDGM, LT, and SLT codes under the low coding rate condition in the satellite-to-ground laser downlink channel. The system block diagram and the simulation condition are shown in Fig. 3 and Table I, respectively, where c and δ in RSD in Table I are the control parameters of degree probability. The channel model is the four state Markov model described in Section II. Fig. 4 shows the PER performance versus the number of codeword W in one interleaver as shown

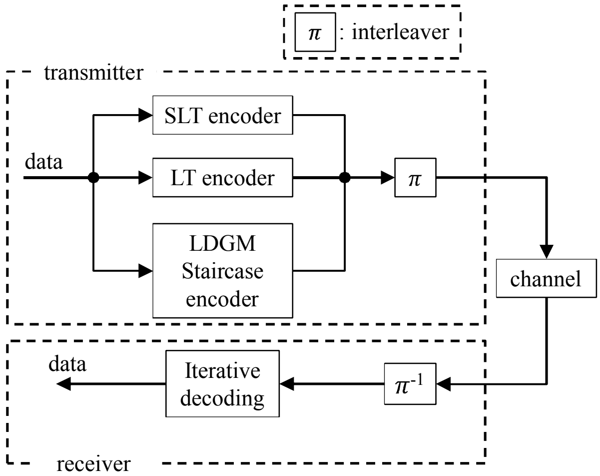

Fig. 3 System block diagram.

Table I. Simulation conditions.

Coding scheme		LT, SLT, LDGM staircase
Decoding algorithm		Iterative decoding
Galois field		GF(2^8)
Num. of information symbols: K		240 symbol
Code length : N		1200 symbol
1 packet length		N
Code rate: R		0.2
Weight parameter	LT	RSD, (c, δ)=(0.07, 0.05)
	SLT	IRSD, (c, δ)=(0.07, 0.05)
	LDGM	(row w_j, column w_k)= (8, 2)
Interleaver		random interleaver
Interleaver size		$N \times W$ (W=20, 40, …, 220)
Channel model		Four-state Markov
Transition probability		P_{S0}=0.27, P_{S1}=0.06, P_{S2}=0.24, P_{S3}=0.05
Transmission rate		10 Mbps
Transition time		0.05 [ms]
Erasure bits per unit time		500 bit (63 symbol)

in Fig. 2. In the relatively small interleaver with W=20 to 160, SLT code has the best PER of three codes. In general, it was confirmed that the SLT code has better performance than LT code under low rate conditions because SLT code has many degree=1 symbols which makes the iterative decoding more effective. The performance of LDGM Staircase code is degraded with small interleaver because it is difficult to find the good low rate configuration in LDPC code and LDGM Staircase code has correlated with adjacent symbol by $\mathbf{H_P}$ that makes weak for remained bursty erasure with small interleaver.

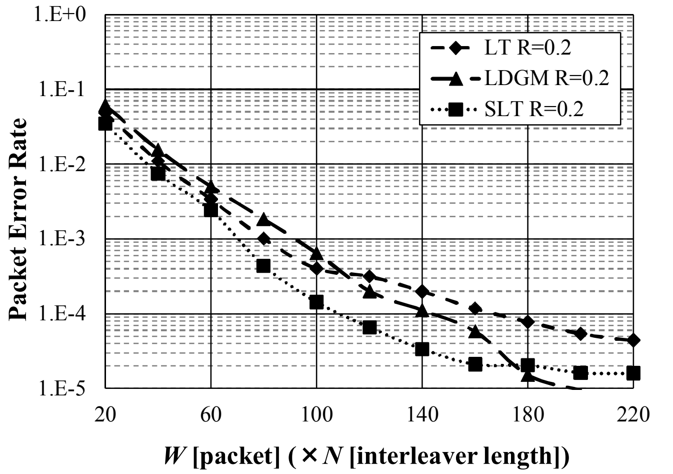

Fig. 4 PER performance versus number of codewords in interleaver.

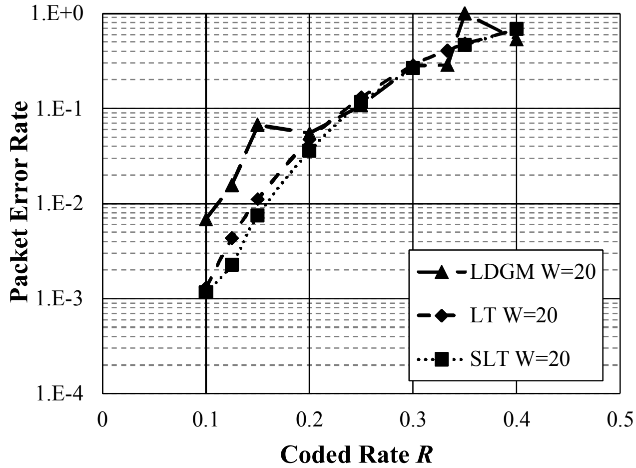

Fig. 5 PER performance versus code rate when interleaver length is $N \times W$ =1200× 20 symbols.

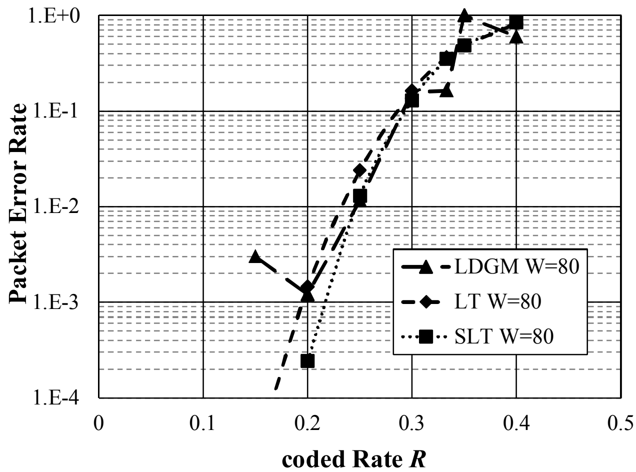

Fig. 6 PER performance versus code rate when interleaver length is $N \times W$ =1200× 80 symbols.

Table II. Configuration of check matrix in LDGM code on each coding rate.

Code rate: R	Row and column weights (w_j, w_k)	Num. of information length: K
0.1	(18, 2)	120
0.125	(14, 2)	150
0.15	(17, 3)	180
0.2	(8, 2)	240
0.25	(6, 2)	300
0.3	(7, 3)	360
0.333	(4, 2)	400
0.35	(13, 7)	420
0.4	(3, 2)	480

In fact, when W is over 180, the performance of LDGM becomes better than SLT. Figs. 5 and 6 show the PER versus coding rate with the interleaver size of W=20 and 80, respectively. The code length is fixed at N=1200 and the information length is changed according to the coding rate. The code configuration such as row and column weights and information length of LDGM code is listed in Table II. It is confirmed that the LDGM has discontinuous performance because of discrete code configuration as Table II, and that the SLT has the best PER performance below R=0.2.

VI. Conclusions

We investigated suitable channel coding schemes for the downlink satellite-to-ground channel and the performances of LDGM Staircase, LT, and SLT codes were compared. From numerical results, it was found that SLT code had the best PER performance when the interleaver size was not large and advantage of SLT code was obtained with the coding rate below R=0.2.

In future studies, an adaptive transmission scheme of SLT code in terms of coding rate and interleaver size will be considered.

Acknowledgment

This research was partially supported by the Scientific Research Grant-in-aid of Japan No. 23560450. The authors wish to thank all of them for their support.

References

[1] M. Toyoshima, H. Takenaka, C. Schaefer, N. Miyashita, Y. Shoji, Y. Takayama, Y. Koyama, H. Kunimori, S. Yamakawa, E. Okamoto, “Results from Phase-4 Kirari Optical Communication Demonstration Experiments with the NICT Optical Ground Station (KODEN),” Proc. AIAA Int’l Commun. Satellite Systems Conf., ICSSC2009-3.4.2, CD-ROM 9 pages, Jun. 2009.

[2] Y. Yamashita, E. Okamoto, Y. Iwanami, Y. Shoji, M. Toyoshima, Y. Takayama, “An efficient LDGM coding scheme for optical satellite-to-ground link based on a new channel model”, Proc. IEEE Globecom, Dec. 2010.

[3] Japan Aerospace eXploration Agency, “Advanced Land Observing Satellite-2 (ALOS-2)”,
[Online]: http://www.jaxa.jp/projects/sat/alos2/index_e.html

[4] M. Toyoshima, H. Takenaka, Y. Shoji, Y. Takayama, Y. Koyama, and M. Akioka, "Small Optical Transponder for Small Satellites", International Symposium on Communication Systems, Networks and Digital Signal Processing, 2nd Colloquium in Optical Wireless Communications at the IEEE International Conference (CSNDSP10), OWC-10, Northumbria University, United Kingdom, July 21-23 (2010).

[5] Advanced Engineering Services Co.,Ltd., “AES SATTELLITE - SOCRATES - ”,
[Online]: http://www.aes.co.jp/product/pdf/socrates_hp_e.pdf

[6] V. Roca, and C. Neumann, “Design, Evaluation and Comparison of Four Large Block FEC Codes, LDPC, LDGM, LDGM Staircase and LDGM Triangle, plus a Reed-Solomon Small Block FEC Codec,” INRIA Research Rep. RR-5225, Jun. 2004.

[7] E. Okamoto, T. Kyo, H. Inoue, Y. Shoji, Y. Takayama, and M. Toyoshima, “Perspectives of channel coding for satellite laser communications,” IEICE Tech. Reports, SAT2013-5, pp.25-30, May 2013 (in Japanese).

[8] H. Takenaka, M. Toyoshima, Y. Takayama, Y. Koyama, M. Akioka, “Experiment plan for a small optical transponder onboard a 50 kg-class small satellite”, Proc. International Conference on Space Optical Systems and Applications (ICSOS), pp.113-116, May, 2011.

[9] H. Takenaka, et al, “Study on Coding Parameter for Small Optical Transponder”, Proc. International Conference on Space Optical Systems and Applications (ICSOS), May 2014.

[10] Michael Luby, “LT Codes,” 43rd Annual IEEE Symposium on Foundations of Computer Science, pp. 271-280, 2002.

[11] T. D. Nguyen, L. L. Yang, and L. Hanzo, “Systematic Luby transform codes and their soft decoding,” in IEEE Workshop on Signal Processing Systems, pp. 67–72, 17-19 Oct. 2007.

[12] C. Sasaki, O. Kobayashi, T. Hasegawa, S. Ano, and T. Hasegawa, “Add-on Request Method for Multicast Content Distribution using LT codes,” IPSJ SIG Notes, 2006-GN-58, pp. 139-146, Jan. 2006 (in Japanese).

[13] R. Y. S. Tee, T. D. Nguyen, L. L. Yang and L. Hanzo, “Serially Concatenated Luby Transform Coding and Bit-Interleaved Coded Modulation Using Iterative Decoding for the Wireless Internet,” in Vehicular Technology Conference, vol. 5, (Melbourne, Austrialia), pp. 2494–2498, Spring 2006.

[14] T. D. Nguyen, L. L. Yang, S. X. Ng and L. Hanzo, “An optimal degree distribution design and a conditional random integer generator for the systematic Luby Transform coded wireless internet,” Submitted for WCNC 2008, http://eprints.ecs.soton.ac.uk/14587.