Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 10-3, Ajaccio, Corsica, France, October 9-12 (2012)

A LT-Based Multi-Rate Transmission Scheme with Fast Decoding for Satellite Laser Communication

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***Abstract*— There are expanding demands for satellite laser communications because it enables an extremely high capacity. The satellite laser communication, however, has several technical problems to be solved. One of them is air scintillation which causes a burst decreasing of receive optical power, resulting in poor transmission performance. To tackle this problem, a forward error correction (FEC) is used in general and the efficient FEC for the satellite laser communication is required. In particular, the fast decoding is important since the transmission rate will be very high. In this case, it is known that the application of erasure channel is effective in which the channel condition is simplified into two states: correct or erasure. If the receive power is sufficiently high, the receive symbol is treated as "correct", otherwise "erased". Then, an erasure code in which the fast decoding is available is applied and the erased symbol is recovered. In addition, a multi-rate transmission is also effective in satellite communication to balance the quality and rate of transmission, e.g., the adaptation for data contents, weather at the earth station, or link distance. Therefore, we propose a Luby Transform (LT)-based multi-rate transmission scheme with fast decoding for satellite laser communications. The performance of the proposed scheme is evaluated through computer simulations.**

Keywords-component; luby transform; multi-rate transmission; optical satellete communication; iterative decoding; fast decoding;

I. INTRODUCTION

Free-space optics (FSO) has an ultra-high channel capacity because of unlimited bandwidth. Its frequency is around THz band and is wideband that means rich frequency resources.

National institute of information and communications technology (NICT) has carried out the satellite laser communication experiments between Optical Inter-orbit Communications Engineering Test Satellite (OICETS) and the earth station in 2006.

From the results, it is confirmed that the bursty degradation of optical reception power occurs due to air scintillation, resulting in the degradation of communication quality [1]. This satellite-to-ground laser channel is modeled as a Markov model in [2]. In addition, NICT is developing a laser communication terminal named as Small Optical Transponder for micro-satellite (SOTA) and plans to demonstrate several laser satellite-to-ground experiments [3].

In [2], the laser propagation channel is modeled as a burst erasure channel, where a sufficiently high threshold is introduced and the received power above that is considered as correct reception, otherwise considered as erasure, thus, an efficient channel coding technique is needed for this channel.

In general, the combination of Forward Error Correction (FEC) and Automatic Repeat-reQuest (ARQ) are used. However since the altitude of OICETS is around 610km, ARQ doesn't effectively work due to long propagation delay. Then, a strong FEC is needed. Furthermore, in laser satellite-to-ground channel, the prospective status will be changed according to the elevation angle at earth station, propagation distance, and the weather. Therefore, the transmission scheme having multiple properties of transmission quality and speed will be effective. As one of those schemes, a dual-rate transmission scheme using two configurations of Low-density Generator Matrix (LDGM) code as long erasure codes for the laser satellite-to-ground channel has been proposed in [4]. However, the decoding of LDGM codes can be started after all codeword is received, and the large complexity is needed in some decoding algorithm of LDGM codes [5]. It may result in a long decoding delay. In addition, multi-rate transmission more than three and its rate-estimation and decoding scheme is not considered.

Therefore, in this paper we propose a multi-rate Luby Transform (LT) code for the satellite laser channel [6]. LT code is an error correction code in which a sequential decoding before all codeword reception can be done, and this property is utilized. Also the multi-rate more than three is considered and the example of four-mode transmission is demonstrated. In the following, the performance of LT code in the satellite laser channel is numerically analyzed in Section 2. The multi-rate LT code, its decoding algorithm, and the performances are introduced is in Section 3, and the conclusion is remarked in Section 4.

II. PERFORMANCE OF LT CODES IN SATELLITE-TO-GROUND LASER CHANNEL

A. LT codes

LT code is a family of Low-density Parity Check (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. 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 [6] 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) and q is a natural number. 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

$$c_l = \sum_{j=1}^{d_l} m_{h_{lj}} \tag{1}$$

where $1 \le d_l \le K$ and ^{T} describes the transpose. In particular, when p=1, Eq. (1) 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.

B. Effect of interleaving in four-state Markov laser channel

In four-state Markov model of satellite-to-ground laser channel in [2], there are error-free states denoted as Line-of-sight (LoS), all-lost states denoted as None-lone-of-sight (NLoS) below the threshold. Each LoS and NLoS has high-transition state and low-transition state. Thus, the Markov model consists of four states. From the OICETS experiment results of NICT, the transition interval is 50ms, which becomes 50bit burst at 1Mbps binary modulation. It is shown in [2] that the block transmission with an interleaver is effective to randomize the burst erasure caused by this channel. However, it needs a large storage for interleaving in both the transmitter and the receiver, and the process delay will be large. On the other hand, LT codes do not need to have the interleaver since the random effect is included in the encoding rule in principle. Hence, it is expected that the process delay is improved and the system complexity is reduced. In the next subsection it is shown that the interleaver can be omitted in LT codes in the satellite laser channel.

C. Performance of LT code in four-state Markov channel

To confirm the error correction ability of LT codes in four-state Markov channel, we numerically analyze the Packet Error Rate (PER) performance versus the code length. The transmission system is drawn in Fig. 1, the simulation conditions are listed in Tab. 1, and the results are shown in Fig. 2. The performance of LDGM Staircase code at the same condition is also plotted for comparison [4]. From the result, in can be seen that the PERs of LT code are identical regardless of the interleaver, and that the LT code outperforms the LDGM code according to the expansion of code length. It may come from the difficulties of optimal weight configuration of LDGM code at lower-rate. As a result, the LT code has relatively better performance.

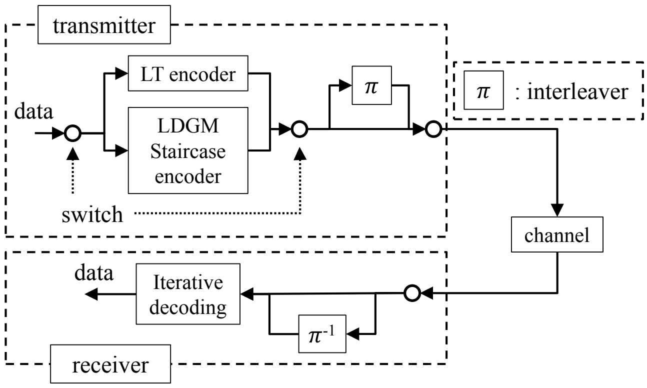

Fig. 1 Simulation model of code comparison.

Tab. 1 Simulation conditions of code comparison.

Code	LT	LDGM Staircase
Decoding scheme	Iterative decoding	
Galois field	GF(2^8)	
Information length : K	300 - 4500 symbol	
Code length : N	1200 - 18000 symbol	
1 packet length	N symbol	
Code rate : R	0.25	
Parameter	Robust Soliton Distribution (c, δ)=(0.07, 0.05)	Weights of (column, row)=(6, 2)
Symbol interleaver	Srandom interleaver, S=5	
Interleaver length	1 packet	
Tramsmission rate	1 Mbps	
Channel	four-state Markov model [2]	
State transmission probability	P_{S0}=27%, P_{S1}=6%, P_{S2}=24%, P_{S3}=5%	
Channel state duration	50 bit	

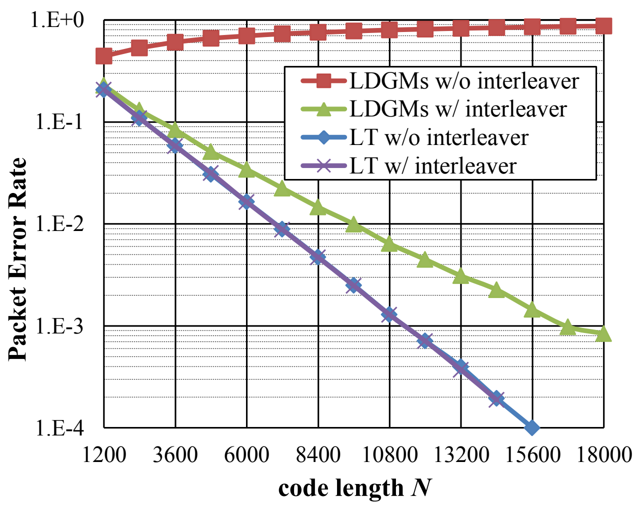

Fig. 2 Performance comparison of erasure codes versus code length in four-state Markov model.

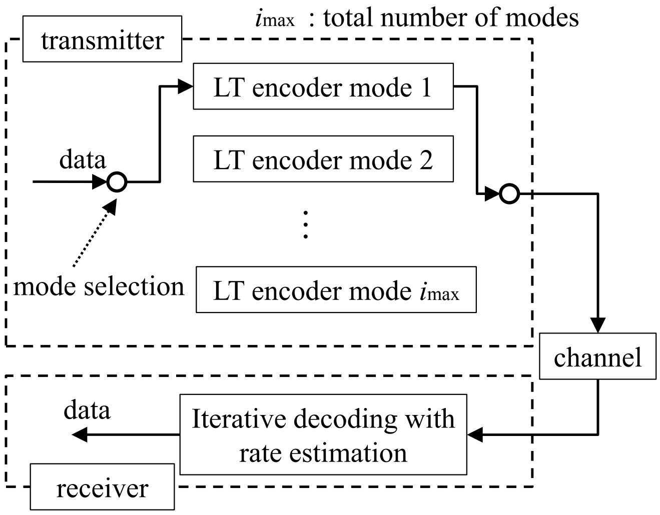

Fig. 3 Block diagram of multi-rate LT codes transmission.

III. MULTI-RATE LT CODE TRANSMISSION

Multi-rate transmission is an adaptive transmission scheme in which the transmitter changes the transmission rate (called 'mode') from prepared multiple code settings according to some states [4]. In this study no preamble nor side-information transmission is assumed so that the receiver needs rate-estimation function using only the received codeword. The multi-rate LT codes transmission and its rate-estimation algorithm enabling more than three modes whose block diagram is illustrated in Fig. 3 are considered in this section.

A. Proposed rate-estimation scheme using LT codes in the decoder

It is assumed that one of the multi-rate codewords is received in the receiver. The rate-estimation is conducted sequentially using the syndromes (described below). The syndrome of specific mode is calculated using the received codeword and the result whether that mode is correct or not is determined. If that mode is determined as incorrect, other mode estimation is conducted. This principle of rate-estimation is the same among multi-rate linear codes such as LDGM code. However, multi-rate LT codes have a property of simultaneous processing of codeword reception and rate-estimation. The algorithm is described in the following.

Here, it is assumed that the number of modes is i_{max}, the information symbol length of mode i ($1 \le i \le i_{max}$) is K_i, and mode i estimation is started now. When the syndrome of mode-i LT code is $\mathbf{s} = \{s_1, \ldots, s_{K_i}\}$, l-th symbol of the syndrome s_l is given by

$$s_l = c_l - \sum_{j=1}^{d_l} m_{h_{lj}} \quad (2)$$

In the beginning of the codeword reception in the receiver the decoded information $\mathbf{m} = \{m_1, \ldots, m_{Ki}\}$ is almost unknown and after several reception and iterative decoding, the calculation of (2) is enabled and the syndrome $\mathbf{s}$ will be obtained. If the syndrome is calculated with the prior-information of correct mode i, it is obvious that $s_l = 0$ and $\mathbf{s} = \mathbf{0}$ are obtained. However, if the syndrome is calculated with mismatched prior information, d_l and h_{lj} are not correct and $s_l \neq 0$ is obtained at any l. Thus, when $s_l \neq 0$ is detected, the mode estimation is switched to another mode other than i and the algorithm is restarted. Hence, the sequential rate-estimation with decoding is conducted.

B. Decoding algorithm with proposed rate-estimation

The proposed decoding algorithm is composed with the rate-estimation as follows. The rate-estimation is conducted in ascending order from mode 1 to i_{max}, and if $s_l \neq 0$ is detected at mode i, i is incremented and next search is restarted. If the decoding is completed with $\mathbf{s} = \mathbf{0}$, the mode i is determined and the decoded result is output. In the case that the syndrome cannot be calculated due to the remained erased symbol in iterative decoding, mode i is output as the result and the algorithm is terminated for calculation complexity reduction. The flowchart of this proposed scheme is illustrated in Fig. 4. It can decode the received codeword more than three modes other than the conventional scheme in [4]. The detailed algorithm is described in the following. Here, N' is the received symbol length used for decoding calculation.

(a1). Let $i = 1$ and the iterative decoding is started after one symbol reception ($N' = 1$).

(a2). If all information symbols are decoded, go to (a6).

(a3). If $i \neq i_{max}$, the iterative decoding is conducted until any of syndrome s_l can be calculated and go to (a5). If $i = i_{max}$, the iterative decoding is conducted until terminated and go to (a6).

(a4). It no syndrome s_l can be calculated even after the iterative decoding is terminated, go to (a6).

(a5). If $s_l \neq 0$, $i = i+1$ and return to (a2). If $s_l = 0$, return to (a2).

(a6). Determine the transmitted mode is mode i and end the algorithm

By this algorithm, the rate-estimation of multi-rate LT codes can be achieved with retaining the sequential decoding property of LT. However, it is expected the rate-estimation performance is degraded in highly erased channel since the syndrome is hardly calculated.

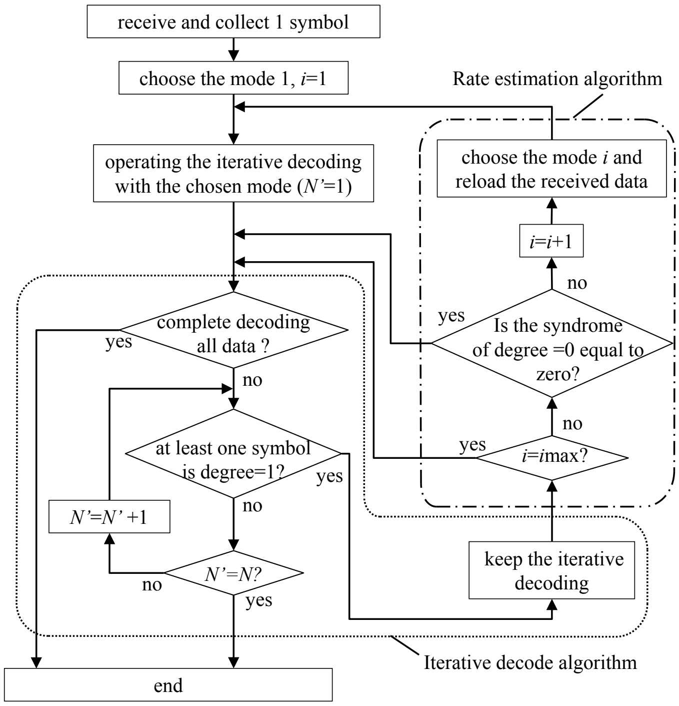

Fig. 4 Proposed algorithm of iterative decoding with rate-estimation.

C. Numerical results

We evaluate the performance of the proposed decoding algorithm. The four-rate LT codes transmission scheme (i_{max}=4) as shown in Fig. 3 is assumed and the simulation conditions are listed in Tab. 2. From the results of Fig. 2, the random erasure channel is assumed in this simulation without loss of generality.

Figs. 5 and 6 show the PER and the average rate-detection error rate (RER) performances versus symbol erasure rate p in the channel, respectively. Here, the rate-detection error is defined as the ratio of incorrect rate-decision between the transmitter and the receiver. In Fig. 5, 'w/ estimation' and '-perfect' mean the case of the proposed algorithm in Fig. 4 and the ideal case in which the rate information is perfectly known to the receiver, respectively. The results of Fig. 5 show that the no degradation of PER occurs with the rate-estimation and it can be said that the multi-rate LT code transmission is achieved without the PER degradation from rate-estimation loss. From Fig. 6, it is confirmed that RER of 1.80×10^{-3} is achieved at p = 0.62. Consequently, it is shown that the proposed algorithm has a good rate-estimation performance enabling more than three modes which doesn't deteriorate the PER.

IV. Conclusion

In this paper, we proposed a multi-rate LT code transmission for adaptive satellite laser communications and its rate-estimation scheme. It was shown that LT codes didn't need to

Tab. 2 Simulation conditions for four-rate LT code transmission.

mode	mode 1	mode 2	mode 3	mode 4
Total number of modes : i_{max}	4			
Generation probability	0.25			
Code	LT			
Decoding scheme	Iterative decoding			
Galois field	GF(2^8)			
Information length : K	720	900	1080	1800
Code rate : R	0.2	0.25	0.3	0.5
Code length : N	3600 symbol			
1 packet length	N symbol			
Parameter	Robust Soliton Distribution, (c, δ)=(0.07, 0.05)			
Decoding algorithm with rate estimation	Fig. 4			
Code length to start decoding	1			
Channel	Random Symbol Erasure			

utilize the interleaver in the satellite-to-ground laser channel and had better performance than LDGM Staircase codes when the code length was long. Then, the performances of four-rate LT codes were evaluated by computer simulations. As a result, PER performances are not degraded compared with the ideal case of rate-information and RER of 1.80×10^{-3} is achieved at p = 0.62, which is high performance.

In future studies, the multi-rate Raptor codes, which is thought to have less calculation complexity than LT codes, and higher-performance rate-estimation scheme will be considered.

ACKNOWLEDGMENT

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

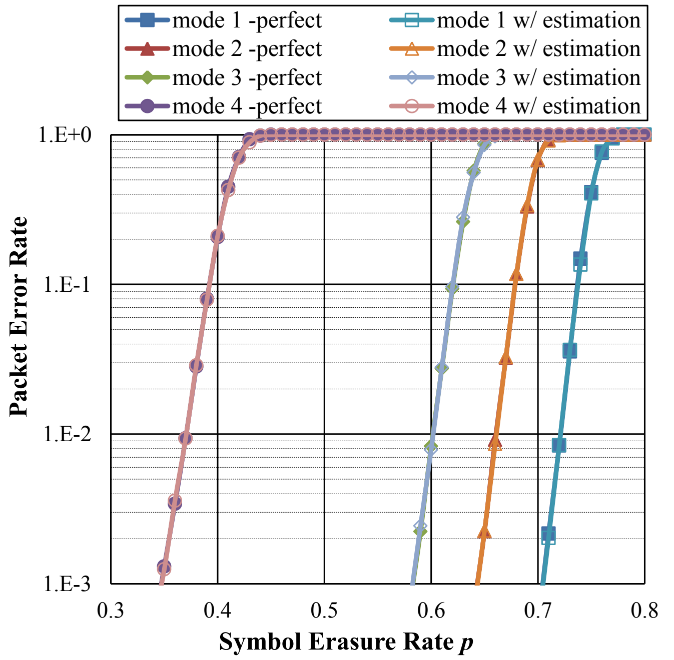

Fig. 5 Packet error rate performance of four-rate transmission system with LT code.

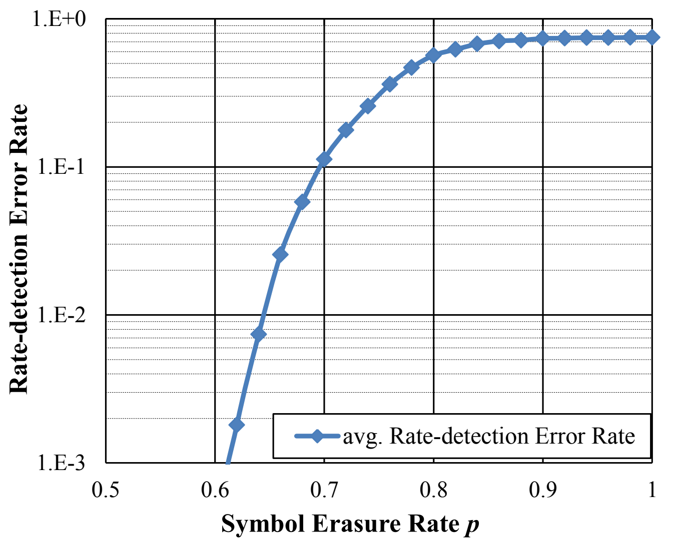

Fig. 6 Average rate-estimation error performance of the proposed algorithm.

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