Multi-rate low density generator matrix code for satellite laser communications

Hirotaka Matsuo†, Eiji Okamoto†, Yasunori Iwanami†, Yozo Shoji‡, Morio Toyoshima‡, and Yoshihisa Takayama‡
† 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 Japan
E-mail: okamoto@nitech.ac.jp

Abstract—**We propose a new transmission scheme of multi-rate low density generator matrix (LDGM) code suitable for optical satellite communications. Since the proposed scheme doesn't utilize a preamble transmission of the rate information nor the repeat request scheme, a long feedback delay in the satellite link and a decrease of transmission efficiency can be avoided. Then, an adaptive rate transmission only with forward error correction (FEC) is achieved and the transmitter can choose the quality or the rate-efficiency of transmission from the transmitter-side state. In the receiver, an exact rate-decision and decoding are conducted without the preamble. It is shown that the proposed scheme is effective in the satellite-to-ground optical link by the computer simulations.**

Keywords-low density generator matrix code; mluti-rate transmission; optical satellete communication; iterative decoding.

I. INTRODUCTION

There exists a growing demand for higher-rate wireless network because of the diffusion of high-capacity communication systems. A free-space optical communication is one of the schemes attracting attention to realize it and the space optical communication using satellites is regarded as a strong candidate. A satellite laser communication is not band-limited as of the radio frequency and is easy to achieve the high-capacity. Moreover, it has an advantage of wide-area connectivity, stability for disasters, and security of communication because of an optical-beam directivity. A small unit can be composed by the use of optical circuit. The optical high-rate network can be achieved not only in near earth but also in deep-space.

However, the satellite laser communication needs a precise optical pointing between the transmitter and the receiver due to its strong directivity, resulting in high technology requirements, and the satellite laser communication system has not widely used yet. The National Institute of Information and Communication Technology (NICT) has succeeded this optical satellite experiment between a low earth-orbital (LEO) satellite, Optical Inter-orbit Communications Engineering Test Satellite (OICETS) , and the ground station in 2008 [1]. We proposed a channel model of the atmospherical satellite-to-ground optical link by analyzing the NICT's experimental results [2]. This channel model is a four-state erasure channel whose erasure is assumed to occur due to air scintillation, laser pointing error, and so on. We also showed in [2] that an low-density generator matrix (LDGM) code with an iterative decoding was effective for this channel.

On the other hand, the quality of service (QoS) on the wireless transmission is usually dependent on its contents. For example, none of bit error is acceptable in the data transmission while a faster transmission is desirable even if some bit error occurs in the stream transmission of voice or video. Thus, the adaptive rate transmission is an effective scheme. In general, to conduct the adaptive transmission, data are packetized and the preamble that has the rate and channel coding information is added in the beginning of the packet. In the receiver, the preamble is first decoded and the decoding configuration is switched adaptively. In addition, when the decoding error occurs, a repeat request is fed back to the transmitter as necessary. However, the addition of preamble makes the rate-efficiency lower and further, the retransmission is usually not effective in the satellite communication due to a long delay. For example, the altitude of OICETS was about 610 km whose round-trip time became 4.1 ms or larger. It is relatively large delay and the large size buffer is needed according to the transmission rate. Hence, the multi-rate transmission should be conducted without the preamble addition nor the repeat request in the optical satellite transmission. In conventional schemes, the multi-rate transmission using low-density parity check (LDPC) code has been proposed [3,4] where the retransmission with feedback is used, and the FEC-based LDGM multi-rate transmission without preamble and feedback has not been considered.

Therefore, we propose a new multi-rate LDGM transmission scheme for satellite laser communications in this paper. In the proposed scheme, the transmitter and the receiver have the same multiple LDGM check matrices. The transmitter selects an appropriate rate for the data to be transmitted and uses the corresponding check matrix to encode. In the receiver, the transmitted rate estimation and decoding are conducted using the received whole data. This simple process enables the adaptive multi-rate transmission without preamble and retransmission. Additionally, the use of LDGM encoder and the iterative linear decoding algorithm enable lower calculation complexity compared with LDPC code. This calculation mitigation is suitable for the higher-capacity satellite laser communication.

In the following, the proposed multi-rate LDGM encoding and decoding are described in Section 2, and the performances are evaluated in a random erasure channel and in a satellite-to-ground optical channel by computer simulations in Section 3. The conclusion is drawn in Section 4.

II. MULTIRATE LDGM TRANMSMISSION SYSTEM

A. System model

Fig. 1 shows the system model of two-rate LDGM transmission. Although the downlink transmission from satellite to ground is assumed in this paper, the application of the proposed scheme to uplink transmission is straightforward. Hereafter, 'rate' is defined as the coding rate ($0 < \text{rate} \leq 1$). In the transmitter, the rate is selected according to the state which the transmitter can obtain, the data is encoded, and transmitted. As the transmitter-side state, the required quality of data contents, the required transmission rate, the propagation distance preliminarily calculated by the satellite orbit, and the relative velocity of the satellite can be treated. Additionally, a gradual change of channel state such as weather or thickness of clouds can be followed by using a scarce feedback. Hence, the transmission rate is selected by the circumstance whether the quality or the transmission efficiency should be prioritized. In the proposed scheme, the code length N is fixed among two rates and the information length K is different for easy packet synchronization. Since the both rates consist of LDGM codes, the two types of check matrices are prepared in the transmitter and the receiver, and the transmitter encodes data on the selected rate. Here, it is assumed that rate 1<rate 2 for simplicity, no limitation other than the code length N is needed, though. After encoded, a transmission frame is composed with W codewords, interleaved, and transmitted. The codewords on different rates can exist in the same frame.

It is reported that the free-space optical channel can be modeled as a binary channel of correct or erasure due to the strong optical directivity [5]. Thus, this binary channel model is applied in this paper. The symbol interleaver is used to randomize the burst erasure. In the receiver, after de-interleaved, the rate estimation, decision, and the decoding on that rate are conducted. Since no preamble with the rate information is used, all transmission data can be assigned for payload and the transmission efficiency can be raised.

B. Rate-decision and decoding algorithm in the receiver

Since the proposed scheme doesn't utilize a preamble, the receiver estimates and determines the transmitted rate using whole received data. For optimum estimation, it is necessary that the maximum likelihood decoding (MLD) of each rate are conducted, the product sums of conditional probability of information symbols over the received symbols for both rates are calculated, and the rate having the larger product sum is chosen. However, the calculation complexity of the LDGM-MLD gets diverged and thus the MLD is impractical. Therefore, we utilize a sequential rate-decision algorithm as shown in Fig. 2 to decrease the calculation complexity. The rate is estimated simultaneously with the decoding operation. The iterative decoding scheme, a popular LDGM error-correcting algorithm for an erasure channel [5], is adopted and after the iterative decoding, the rate is determined by whether the calculated syndrome is zero or not. In this regard, to prevent the miss-decision where the error is corrected to a neighbor codeword and the syndrome becomes zero, the lower-rate which has strong correlation between codewords and has a lower probability of miss-decision is calculated first.

The iterative decoding is a linear hard-decision decoding scheme. Utilizing the fact that the receiver can detect the erasure position in the received symbols by the measurement of received optical power, the receiver searches a one-symbol erasure case on each row of LDGM parity check matrix, which is equivalent to the generation equation of parity symbol from information symbols. If the one-symbol erasure is found on any rows of check matrix, that erasure can be recovered by the symbol summation of that generation equation (more exactly, symbol subtraction). Then, another one- symbol erasure is searched on other rows. The search and recovery is iterated until there is no one-symbol erasure.

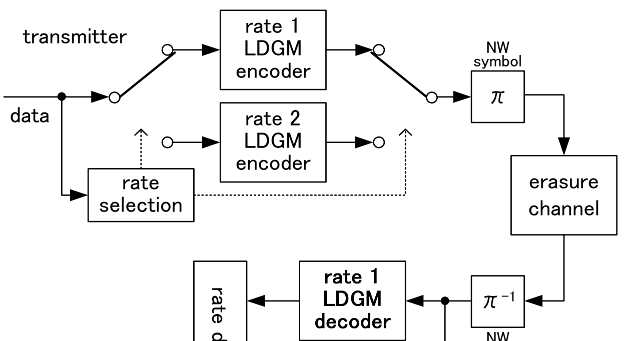

Fig. 1. Multi-rate LDGM system model.

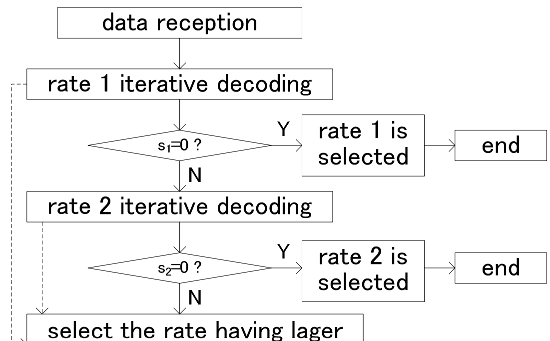

Fig. 2. Algorithm of rate-decision and decoding.

Using this iterative decoding, the proposed algorithm in Fig. 2 is conducted as follows. First, the iterative decoding is done for rate 1 using the received data and after that the syndrome s_1 of rate 1 is calculated. If s_1=0, then the rate is determined as rate 1 and the decoding is terminated. If s_1 is not zero, then the iterative decoding for rate 2 is conducted. If s_2=0, then the rate 2 is selected and the decoding is terminated. If both syndromes are not zero, the rate having the larger number of erasure recovery in iterative decoding is selected and the decoding is terminated. This algorithm enables a half calculation complexity when rate 1 is transmitted and the decoding complexity increase can be restricted.

III. NUMERICAL RESULTS

A. *Performance comparison in random erasure channel*

To confirm the effectiveness of the proposed scheme, the transmission performances are calculated in a random erasure channel with the codeword length per frame W=1. The simulation conditions are listed in Tab. 1. The LDGM staircase code is used and the rate 1 and 2 are set as 0.25 and 0.5, respectively. The code length is 500 and the degree of Galois field is 8. The rate 1 has relatively strong error-correction ability for symbol erasure, while the rate 2 has an increased number of transmission symbols, i. e., larger rate-efficiency. The generation probability of both rates are 0.5 for simplicity and the two types of single-rate LDGM with the same rate and code length are considered as the conventional scheme for comparison. The packet error rate (PER) performance versus the symbol erasure probability p in the channel when the erasure position is perfectly known to the receiver is shown in Fig. 3. Here, the symbol erasure probability is a rate of symbol erasure which occurs in the channel, and one packet means one codeword of N symbols. When the rate-decision error happens in the receiver, one error is counted to the transmitted rate. For example, if the rate 1 was selected in the transmitter and the receiver determined as rate 2, the packet error of rate 1 was counted. As shown in the results of Fig. 3, the multi-rate LDGM transmission is achieved. At more than 0.7 of erasure rate p, both rates have the error rate of almost 1. However, in the lower erasure rate of 0.7, the PER of rate 1 rapidly becomes lower and in the erasure rate of 0.5 or lower, the rate 2 has a gradual improved PER. Thus, the tradeoff between the transmission quality and the rate-efficiency can be

Table 1. Simulation conditions for random erasure channel.

Code	LDGM staircase	
Galois field	GF(2^8)	
Mode	Rate 1	Rate 2
Information length K	125 symbol	250 symbol
Code length N	500 symbol	
Column (j) and row (k) weights	j=6, k=2	j=3, k=3
Code rate	0.25	0.5
Generation probability	50%	50%
Channel	Random erasure	

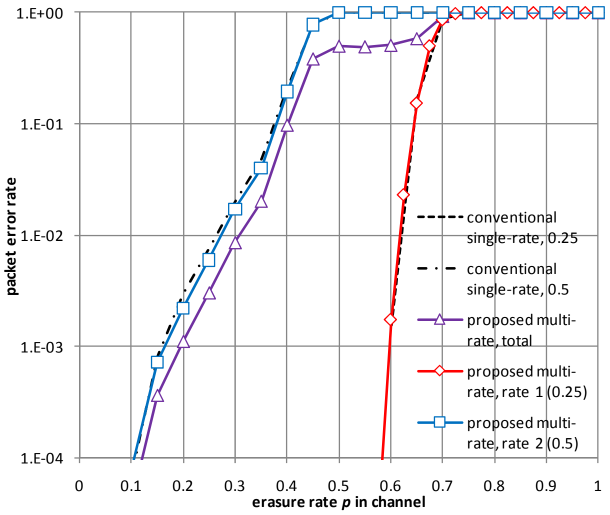

Fig. 3. Packet error rate performance of multi-rate LDGM in random erasure channel.

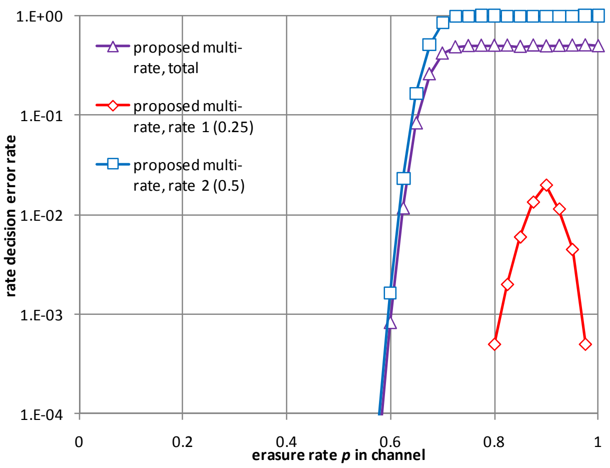

Fig. 4. Rate-decision error rate performance of multi-rate LDGM in random erasure channel.

obtained. Compared with the conventional single-rate LDGM, the proposed scheme has almost the same PER, that means the multi-rate transmission without the preamble and also without the performance degradation is achieved. To confirm this, the rate-decision error on the simulation of Fig. 3 was calculated. The result of Fig. 4 shows that the rate 1 is correctly selected at the receiver under p of 0.8 or lower, although the error is increasing according to p decrease between 0.9 and 1. Since the effective PER is obtained under p of 0.7, no rate-decision error occurs in the effective range of rate 1. Similarly, in rate 2 transmission, under p of 0.6 there is no rate-decision error and in the effective PER range of p of 0.5 or lower the rate is perfectly estimated. Hence, the PER performances of the proposed scheme coincide the single-rate LDGM, and the effectiveness of decoding algorithm in Fig. 2 was shown. This simulation was the example of rates of 0.25 and 0.5 but any pair of rates can be chosen according to the required PER curve and rate-efficiency.

Further, it is expected that more than two rates can be composed in the proposed scheme. The rate-decision will be conducted from the lower rate code but detail configuration will be considered in the further study.

B. Performance comparison in satellite-to-ground optical channel

The performance of the proposed scheme in the satellite-to-ground optical channel is evaluated. Fig. 5 shows the four-state Markov model of OICETS-to-ground channel proposed in [2]. In this model, there are two groups of line-of-sight (LoS) and non-line-of-sight (NLoS). An erasure-free transmission is obtained 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 received optical power in the OICETS experimental results. Since the erasure rate becomes about 60 % in this channel, the rate configuration is set as 0.1 and 0.2 as shown in Tab. 2. The code length is 500 and the generation probability of each rate is 0.5 as well as Tab. 1. The transmission rate is assumed 1.12 Mbps. From

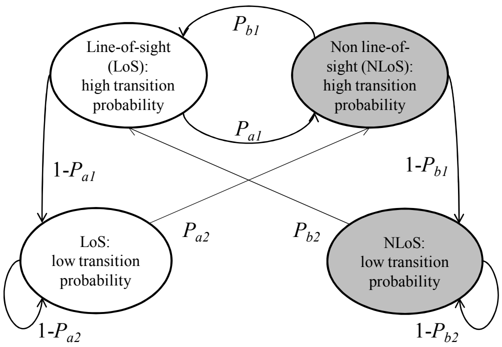

Fig. 5. Four-state Markov model of optical satellite channel.

Tab. 2. Simulation conditions for satellite-to-ground optical channel.

Code	LDGM staircase	
Galois field	GF(2^8)	
Mode	Rate 1	Rate 2
Information length K	50 symbol	100 symbol
Code length N	500 symbol	
Column (j) and row (k) weights	j=9, k=1	j=4, k=1
Code rate	0.1	0.2
Generation probability	50%	50%
Frame length W	1 to 15	
Channel	4-state Markov	
State transition probability	P_{a1}=27%, P_{b1}=24%, P_{a2}=6%, P_{b2}=5%	
Channel condition	LoS : error free NLoS : all lost	
Transmission rate	1.12 Mbps	
Channel state duration	56 bit	
Symbol interleaver	s-random, $S = \frac{\sqrt{2NW}}{3} - 1$	

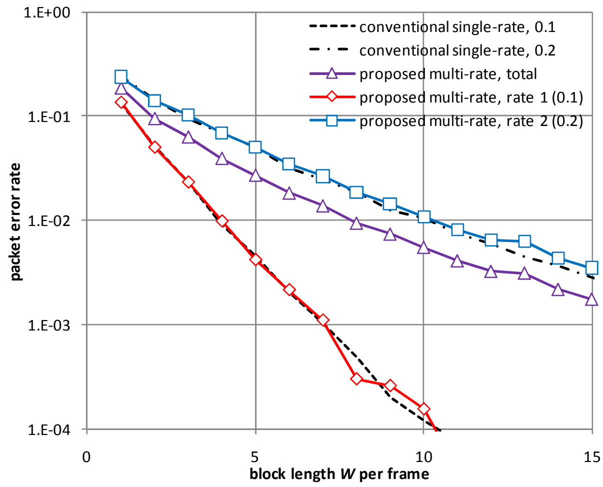

Fig. 6. Packet error rate performance of multi-rate LDGM in satellite-to-ground optical channel.

OICETS experiments the channel coherent time is 0.05 ms and then, the channel fluctuates on every 7 symbols burst (=56 bit). Thus, the PER performance is improved by increasing *W* and expanding one frame length where the interleaver effectively translate a burst erasure into a random erasure. Fig. 6 shows the PER performance versus the block length *W* per one frame. As well as the results in random channel, the multi-rate transmission with different quality and rate is achieved, and also the PER coincides the single-rate transmission. Hence, we can see that the probability of rate-decision error is quite lower. According to *W* increase, the burst erasure changes equivalently into the random erasure and the PER is improved. The PER of 10^{-2} is obtained with *W*=4 at rate 1 and *W*=10 at rate 2, and thus, the multi-rate LDGM transmission with 10^{-2} of PER can be composed for the satellite-to-ground link by the block transmission of *W*=10. By the proposed scheme, the tradeoff between quality and rate-efficiency is obtained without any preamble nor retransmission.

IV. CONCLUSION

In this paper, we proposed the multi-rate LDGM transmission scheme for satellite laser communications which uses an FEC without a preamble nor a repeat request. By preparing multiple check matrices in both the transmitter and the receiver, the multi-rate transmission and decoding were conducted. The receiver uses all received data to determine the transmitted rate and an exact rate estimation was obtained. We applied it into the satellite-to-ground optical channel and the tradeoff between transmission quality and rate-efficiency was shown by two-rate LDGM codes with coding rate of 0.1 and 0.2.

In future studies, the multi-rate more than two, the improvement of rate-decision algorithm, and the following scheme to channel fluctuation without buffer increase will be considered.

ACKNOWLEDGEMENT

The measured data is based on the collaborative research agreement between JAXA and NICT for next generation space laser communication technologies. The authors wish to thank all for their support.

REFERENCES

[1] M. Toyoshima, H. Takenaka, C. Schaefer, N. Miyashita, Y. Shoji, Y. Takayama, Y. Koyama, H. Kunimori, S. Yamakawa, and 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, 9 pages, Jun. 2009.

[2] Y. Yamashita, E. Okamoto, Y. Iwanami, Y. Shoji, M. Toyoshima, and Y. Takayama, “An efficient LDGM coding scheme for optical satellite-to-ground link based on a new channel model,” Proc. IEEE Global communications conference (GLOBECOM), SAC-05-3, 6 pages, Dec. 2010.

[3] M. R. Yazdani and A. H. Banihashemi, "On construction of rate-compatible low-density Parity-check codes," IEEE Communications Letters, vol.8, no.3, pp. 159- 161, Mar. 2004

[4] W. Matsumoto and H. Imai, “A Study on Rate Compatible LDPC Codes, ” Proc. ISITA'04, pp. 529 - 534, Oct. 2004.

[5] V. Roca and C. Neumann, “Design, Evaluation and Comparison of Four Large Block FEC Codecs, LDPC, LDGM, LDGM Staircase and LDGM Triangle, plus a Reed-Solomon Small Block FEC Codec,', INRIA Research Report RR-5225, June 2004.