

## PAPER

# A Markov-Based Satellite-to-Ground Optical Channel Model and Its Effective Coding Scheme

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**SUMMARY** We propose a novel channel model of satellite-to-ground optical transmission to achieve a global-scale high-capacity communication network. In addition, we compose an effective channel coding scheme based on low-density generator matrix (LDGM) code suitable for that channel. Because the first successful optical satellite communication demonstrations are quite recent, no practical channel model has been introduced. We analyze the results of optical transmission experiments between ground station and the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) performed by NICT and JAXA in 2008 and propose a new Markov-based practical channel model. Furthermore, using this model we design an effective long erasure code (LEC) based on LDGM to achieve high-quality wireless optical transmissions.

**key words:** optical satellite communication, optical satellite-to-ground link, Markov model, LDGM code

## 1. Introduction

Developments in high-speed communications are rapid and demands for higher-capacity are still growing. One of the strong candidates is optical transmission. Today, an optical fiber has been used in wired terrestrial networks as a high speed backbone. However, the costs of fiber laying are not negligible and the construction of a global-scale fiber network for higher-capacity is extremely costly. On the other hand, laser satellite communication doesn't require cabling costs because of its wireless transmission. The laser satellite communication easily enables the high-capacity global-scale networks. Moreover, the high-capacity inter-satellite link, deep space link, or inter-planet link can be achieved by the laser satellite communication. Optical wireless transmission doesn't cause interference to radio wave transmission and vice versa, and the sharp directivity of optical wave can keep a security of communication. Hence, the laser satellite communication has lots of advantages over both fiber network and radio wave transmission. However, due to its technical difficulties where a very narrow beam must be established between satellite and earth station, the optical satellite communication has not been in practical use yet. National Institute of Information and Communications Technology (NICT) and Japan Aerospace Exploration Agency (JAXA) has succeeded in satellite-to-ground laser

communication experiment as a world pioneer [1] and continues its research and development.

In order to achieve a high-capacity laser satellite communication, exact modeling of the channel is essential. It assists an optimal design of channel coding for optical satellite links. As the conventional works, the mixed fading models for L-, K-, and Ka-bands [2], K-state Markov model [3], and Wakana model [4] have been established. However, these models are for radio wave channel and they don't match the optical channel in which burst erasures occur due to the sharp directivity of the optical beam. In conventional channel models of laser satellite communications, a few models such as a random erasure channel [5] or a gamma-gamma model considering atmospheric scintillation [6] have been proposed. In those models, however, the burst erasure cannot be precisely expressed. Therefore, we propose a novel optical channel model based on the results of NICT's experiments.

Channel coding is one of the indispensable schemes. In terrestrial wireless communications, strong channel codes such as low-density parity-check (LDPC) code [7] or turbo code [8] have been adopted in various systems. The decoding of those codes incurs large calculation complexity due to the soft iterative decoding algorithm. To achieve a giga-bit class optical satellite communication [9], the use of soft iterative decoding is impractical and a linear encoding and decoding are needed [10]. To solve this problem, we proposed a new long erasure code (LEC) design based on low-density generator matrix (LDGM) code for optical satellite channel in [11]. Enhancing this study, in this paper we consider an application of the repeat request and propose an effective LDGM code with linear decoding.

In the following, the laser satellite communication experiments executed by NICT are briefly reviewed in Sect. 2. The proposed model for optical satellite-to-ground channel is introduced in Sect. 3. The proposed LEC coding system is described in Sect. 4. Numerical results are presented in Sect. 5 and the conclusion is remarked in Sect. 6.

## 2. Outline of Laser Satellite Communication Experiments

NICT carried out the laser communication experiments between an earth station and OICETS in 2008 [1]. Table 1 shows the main specification of OICETS and the outline of experiment is illustrated in Fig. 1. The data transmission ex-

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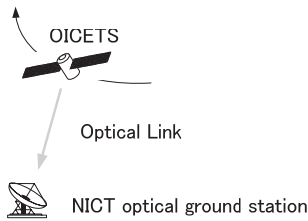
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periments were carried out using both uplink and downlink, where the transmitted data in uplink were once decoded in the satellite, re-encoded and transmitted in downlink. The 15-th pseudorandom noise (PN) sequence is loaded as the contents of transmission data. Although the up- and downlink are used, to derive the one-way channel model, we focused on the downlink as shown in Fig. 1 and analyzed the downlink data. The experiment date and condition are listed in Table 2. OICETS transmitted 847 [nm] laser beam to the ground at 53 [mW] power, the NICT earth station received it, and data are decoded. Figure 2 shows the received optical power waveform in downlink on Exp. A on Table 2. As shown in Fig. 2, the received power changes frequently and in all experiment results there are fluctuation cycles with a

**Table 1** Main specification of OICETS.

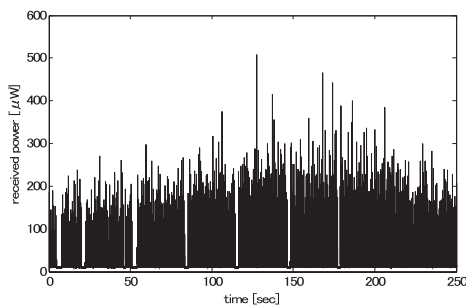
Orbiter	Circular orbit
Altitude	Approx. 610 km
Inclination	Approx. 98 degrees
Wavelength	847 nm
Transmitted power	53 mW
Signal format	RX: Non-return to zero TX: 2-PPM (Manchester)
Data rate	Approx. 50 Mbps



**Fig. 1** Outline of OICETS experiments.

**Table 2** Experiments date and time.

	Date	Weather	Experiment time (JST)	Measurement interval
Exp. A	2008/11/19	clear	02:18:30 to 02:22:01	0.05[ms]
Exp. B	2008/11/21	clear	00:58:33 to 01:03:13	
Exp. C	2008/12/19	clear	02:05:10 to 02:11:05	



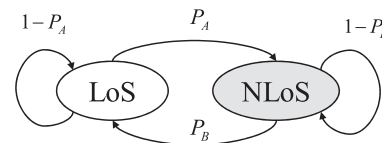
**Fig. 2** Measurement result of received optical power data (Exp. A).

period of about 0.12 [ms]. In the following we derive the channel model using these data.

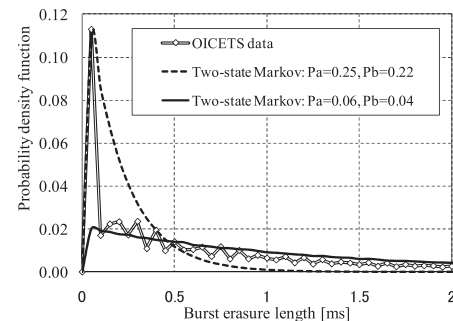
### 3. Channel Model of Optical Satellite-to-Ground Link

#### 3.1 Two-State Markov Model

In satellite communication channels, the received power often changes drastically, which is modeled as Markov model having two or more states. For example, ITU-R recommendation adopts three-state Markov model consisting of LoS (line of sight), Shadowing, and Blockage for UHF-band land mobile satellite channels [2]. K state Markov model and the Wakana model also have several states. Therefore, the optical satellite-to-ground channel model can be reasonably constructed by Markov model. Here, as shown in Fig. 2, the optical satellite channel has burst-like degradation. This degradation comes from various phenomena such as a laser pointing error, tracking error, synchronization error, atmospheric scintillation, and shadowing by clouds. In OICETS experiments, it was calculated that an error-free decoding of 2-pulse position modulation (PPM) could be obtained at more than 23.5 [μW] receive optical power on the earth station [12]. Then, we consider applying the received optical power data in Fig. 2 into two-state Markov model where one state is LoS with 23.5 [μW] or higher, the other is NLoS with less than 23.5 [μW], and the transition probabilities are  $P_A$  and  $P_B$  as shown in Fig. 3. It is assumed for this model that the error-free transmission is obtained in LoS state and the burst erasure occurs in NLoS state. Figure 4 shows the characteristics of probability density function (pdf) versus burst erasure length derived from the experiment result (Exp. A) and the Markov model. Using the experiment results, all burst erasures are picked up, their burst length is measured at the time resolution of 0.05 ms,



**Fig. 3** Two-state Markov model for optical channel.



**Fig. 4** Probability density function of burst erasure length on two-state Markov model and OICETS experiment.

and counted. Then, the probability density is calculated for each burst length. The pdf of Markov model is calculated as well for the same experimental period. From the results, we found that if  $P_A$  and  $P_B$  are set with larger percentages, the peak pdf at shortest erasure of 0.05 [ms] can be identical but pdf of longer erasure doesn't match. Meanwhile, if  $P_A$  and  $P_B$  are set with smaller percentages, the distribution longer than 0.1 [ms] can be identical but the peak at 0.05 [ms] is much smaller. Hence, two-state Markov model cannot represent the practical distribution correctly. The sums of squared error distance between pdfs of experimental results and Markov model are calculated as the degree of coincidence. As a result,  $9.07 \times 10^{-3}$  and  $9.02 \times 10^{-3}$  are obtained for  $(P_A, P_B) = (0.25, 0.22)$  and  $(0.06, 0.04)$ , respectively. They are compared in the next subsection.

### 3.2 Four-State Markov Model

The results of Fig. 4 indicate that an extension from two-state to four-state will be effective where LoS and NLoS have two states each. On two LoS states, one transition probability into NLoS is small and the other is larger. The configuration of NLoS states is the same as LoS. Fig. 5 illustrates the proposed four-state Markov model where LoS and NLoS have high and low transition probabilities, respectively. The high transition state represents the peak pdf and the low transition state represents the tail pdf of longer erasure. It is assumed as well as the two-state model that the error-free decoding is obtained in LoS states and all data are lost in NLoS states. Figure 6 shows the probability density function of OICETS experiment (Exp. A) and four-state Markov model where the transition probabilities are given

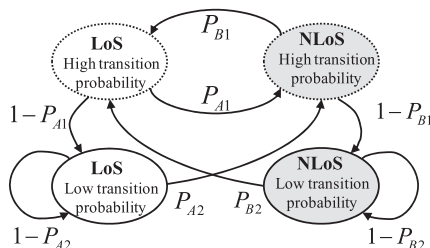


Fig. 5 Four-state Markov model for optical channel.

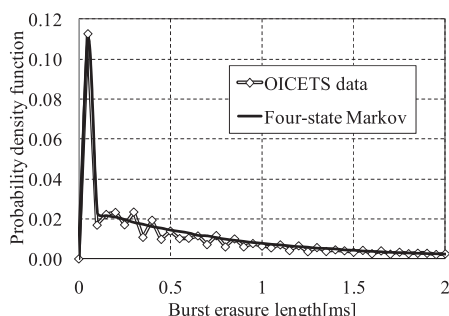


Fig. 6 Probability density function of burst erasure length on four-state Markov model and OICETS experiment A.

by

$$P_{A1} = 0.36, P_{B1} = 0.22, P_{A2} = 0.07, P_{B2} = 0.06 \quad (1)$$

These probabilities are configured by heuristic search. It is found that the four-state Markov model can precisely represent the optical satellite-to-ground channel fluctuation. In the same manner, the probabilities of Exp. B and C are obtained, respectively, by

$$P_{A1} = 0.36, P_{B1} = 0.32, P_{A2} = 0.07, P_{B2} = 0.05 \quad (2)$$

$$P_{A1} = 0.15, P_{B1} = 0.15, P_{A2} = 0.04, P_{B2} = 0.04 \quad (3)$$

Equations (1) to (3) show that the values of each experiment are not so different and the transition probabilities of LoS and NLoS are almost the same or that of LoS is a little higher. As a result, we aggregate the data of Exp. A to C and derive the single transition probabilities. Figure 7 shows the averaged pdf of experiments and the pdf of corresponding Markov model where the transition probabilities are given by

$$P_{A1} = 0.27, P_{B1} = 0.24, P_{A2} = 0.06, P_{B2} = 0.05 \quad (4)$$

The sums of squared error distance become  $7.63 \times 10^{-6}$  and  $1.64 \times 10^{-4}$  for Figs. 6 and 7, respectively, which indicates that the four-state model coincides the experimental results much better than the two-state model. Hence, the precise optical channel model is derived by the four-state Markov model. In the next section, an efficient channel coding is considered using this model.

The generality of this model is considered. The satellite laser communication needs relatively high technologies such as mounting optical units into satellite, an attitude control of satellite, and a laser pointing both in the satellite and in the earth station. Then, up to now there are only three successes of low-earth-orbit (LEO)-to-ground laser transmission, that is, OICETS in 2006 and 2008, NFIRE in 2008, and TerraSAR-X in 2008. Since the proposed channel model is based on the experimental results of OICETS 2008, the channel model is supposed to be changed according to the system configuration of above satellites and/or adopted elemental technologies. However, as there are few experimental results of LEO-to-ground optical transmission, we consider that it is worth proposing the channel model even if

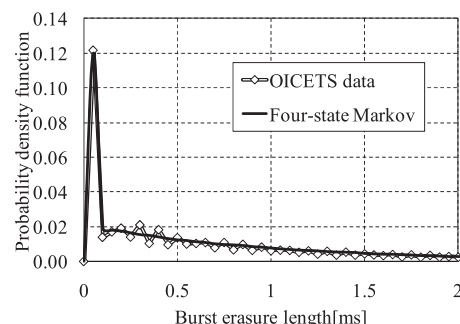


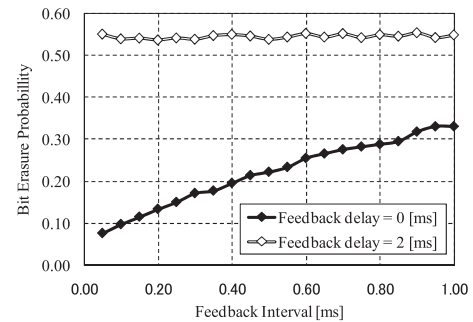
Fig. 7 Probability density function of burst erasure length on four-state Markov model and average of three OICETS experiments data.

it is based on particular experimental results, and generalizing the model will be studied in future works. Meanwhile, the scintillation index and the pdf of received optical power are analyzed in [13] based on OICETS experiments. From the results it is found that the dominant factor of LEO-to-ground channel is an air turbulence, and thus, it is expected that the communication channel model will be similar to the proposed model of this paper regardless of the system configuration. Therefore, an effective channel coding scheme is considered according to the proposed channel model in the following.

#### 4. Coding System for Optical Satellite-to-Ground Link

##### 4.1 Feedback of Channel State Information

According to the proposed satellite-to-ground channel model, we consider an effective space optical transmission system. In general, both forward error correction (FEC) and automatic repeat request (ARQ) are jointly used to achieve high-quality transmissions. Thus, the application of FEC and ARQ are considered here. Since any feedback from the receiver to the transmitter is necessary in ARQ scheme, the channel state information (CSI) feedback is assumed as a simple scheme. Since the transmission probabilities of  $P_{A2}$  and  $P_{B2}$  in low-transmission states are small, long bursty erasure or bursty error-free occur. During the long NLoS state all symbols are lost and if the transmission is interrupted in this period, the efficiency of transmission power can be raised. Fortunately, in the receiver, the channels states can be estimated by the received optical power observation and the CSI feedback will raise the power efficiency. Hence, we consider the ideal CSI feedback system in 4-state Markov channel where data are transmitted only in LoS states on 1 M-bps rate and calculate bit erasure probabilities without channel coding. Figure 8 shows bit erasure probability versus CSI feedback interval with the parameter of feedback delay. In the vertical axis, the bit erasure probability is calculated by the ratio of erasure bits for all transmitted bits. As the delay time increases, the number of transmitted bits in NLoS status increases, resulting in erasure in the receiver and this ratio is increased. From the results, we can see that in the case of no delay, the erasure probability can be lower, say, 0.1 of erasure can be obtained with 0.1 [ms] feedback. This erasure can effectively be recovered by a LEC. However, it is impossible to return the feedback information without delay. The delay of OICETS altitude on Table 1 is about 2 [ms] and in this case the bit erasure probability becomes over 0.5, which cannot be improved by any periods of CSI feedback as shown in Fig. 8. This is because the CSI delay is over the average NLoS period. Therefore, on fast transmission rate, the repeat request scheme doesn't work well in the satellite-to-ground optical communication. Because of the same reason, an error detection scheme is insufficient and FEC schemes are needed on this link.



**Fig. 8** Erasure probability of the received signal versus CSI feedback interval.

##### 4.2 LDGM Code

It was clarified that a strong FEC was indispensable in laser satellite communications. The LDPC code and turbo code are known as the strong FEC in the AWGN channel. However, these codes cannot obtain a large coding gain in a burst erasure channel like the four-state Markov model. Thus, LEC which effectively corrects data in burst erasure channel is applied as FEC. Non-binary Reed-Solomon (RS) code [10] and Vandermonde matrix-based code on  $GF(2^n)$  of  $n > 1$  [14] are often used as LEC for the wireless optical channel. However, the code length is limited under  $2^n - 1$  in RS and Vandermonde codes so that these codes cannot be directly applied for longer erasure channel. Therefore, in this study we adopt a non-binary LDGM code in Galois field  $GF(2^n)$  which recover  $n$  bits at once. The code length of LDGM can be extended more than  $2^n$  according to a parity check matrix. LDGM code is a family of low-density parity check (LDPC) code and can be encoded and decoded only using the parity check matrix. Figure 9 illustrates a simple example of parity check matrix  $\mathbf{H}$  with code length  $N = 10$  and information length  $M = 6$ . Figures 10 and 11 show the improved versions of LDGM, named LDGM Staircase and LDGM Triangle, respectively [10]. Adding 1 at right part of parity check matrix, the coding gain is increased. The operation of encoding and decoding is the same as LDGM code. As shown in the example of Fig. 9, the column and row weights in the left part are assumed as  $j$  and  $k$ , respectively and the right part of  $\mathbf{H}$  is a unit matrix. All nonzero elements on  $S_1$  to  $S_6$  are assumed as "1" for simplicity without loss of generality but can be any elements in  $GF(2^n)$ . Then, the relationship between  $N$ ,  $M$ ,  $j$ , and  $k$  are given by

$$N = M + \frac{jM}{k} \quad (5)$$

In encoding, using the relationship of each row, the parity symbol is calculated sequentially. For example,  $P_7$  in Fig. 9 is calculated by using

$$S_2 + S_4 + S_6 + P_7 = 0 \quad (6)$$

Similarly in decoding, the erasure position information is utilized and an iterative erasure recovery is executed. In

$$\mathbf{H} = \begin{bmatrix} S_1 & \dots & S_6 & P_7 & \dots & P_{10} \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Fig. 9 Example of LDGM parity check matrix.

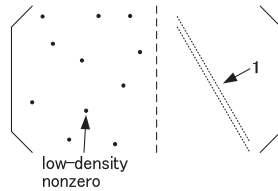


Fig. 10 Parity check matrix of LDGM Staircase code.

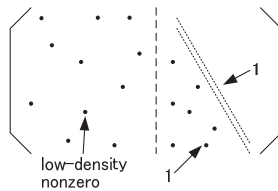


Fig. 11 Parity check matrix of LDGM Triangle code.

practice, the erasure position is obtained by the measurement of received optical power. If the received power is under the threshold, that symbol is marked as erasure. After marking the erasures, all check node equations are calculated. If none of erasure occurs, then, all equations (i.e. syndromes) output zero and the received data are correct. If some erasures occur and if there is only one symbol lost in any one equation (e.g.,  $S_6$  in (6)), that symbol is recovered by algebraic calculation (e.g.,  $S_6 = S_2 + S_4 + P_7$ ). By iterating this calculation at all check nodes, two or more lost symbols in the single equation can be recovered. When all erasures are recovered or there is no single erasure in one equation, the decoding is finished. This operation is called iterative decoding. Since only the sum operation is needed, the computational complexity is not high even for long-length code.

As the more powerful decoding, Gaussian elimination (GE) has been proposed in [15], which is one of solving schemes of simultaneous linear equations. GE can recover the multiple erasures at the same time and has a larger recovering capacity than linear iterative decoding, but also has a higher decoding complexity. Therefore, a hybrid decoding has also been proposed in which the decoding is first done by the iterative decoding and only if there are any residual erasures, GE is carried out. We compare the performances of both decoding algorithms.

#### 4.3 Coding System for Four-State Markov Channel

As described above, the code length of LDGM can be freely

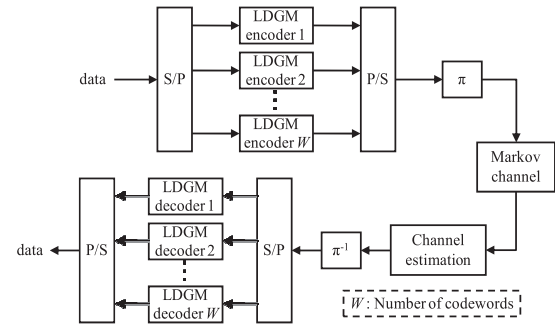


Fig. 12 Coding system for optical satellite-to-ground channel.

extended. An error-free transmission can be obtained on the optical satellite channel when the code length of LDGM is longer than the burst erasure period. However, with an extremely long LDGM, the memory space of  $\mathbf{H}$  will be huge and the complexity of encoding and decoding becomes quite high, and thus, such long LDGM is not practical. Especially, it is critical in GE scheme. GE needs the calculation complexity of  $O(i^3)$  for the number of erasure  $i$  [15]. If we assume there are  $10i$  erasures in one packet, the calculation complexity becomes  $O(\{10i\}^3)$  with one LDGM code in one packet. When one packet consists of 10 shorter LDGM codes, the minimum calculation complexity becomes  $O(10i^3)$  which is much smaller than one longer LDGM code. Therefore, we consider the concatenation of  $10^3$ -length LDGM codes and make an equivalently longer code than burst erasure caused in the channel. It is empirically known that the LDGM codes effectively recover data until 0.1 less probability of random erasure than the code redundancy [10]. Using this fact, an interleaver is inserted just before the channel, and the burst erasure is transformed into the random erasure. Then, the code design can be concentrated just into the configuration of code rate. In the receiver, the detection of erasure is obtained by the measurement of received optical power before de-interleaver and it is also de-interleaved.

Based on the above consideration, we use an interleaver-based coding system for the optical satellite-to-ground channel as shown in Fig. 12. The transmit data are serial-to-parallel transformed and coded by  $W$  LDGM encoders. After that, the coded symbols are parallel-to-serial transformed, interleaved, and transmitted. In the receiver, the position of erasure is estimated by the measurement of received power, and the received symbols are de-interleaved to change the burst erasure into the random erasure. Then, after serial-to-parallel transformed the received symbols are decoded by  $W$  decoders with the obtained erasure position information. Hence, the long burst erasure is changed to random erasure and LDGM codes effectively recover the erasure.

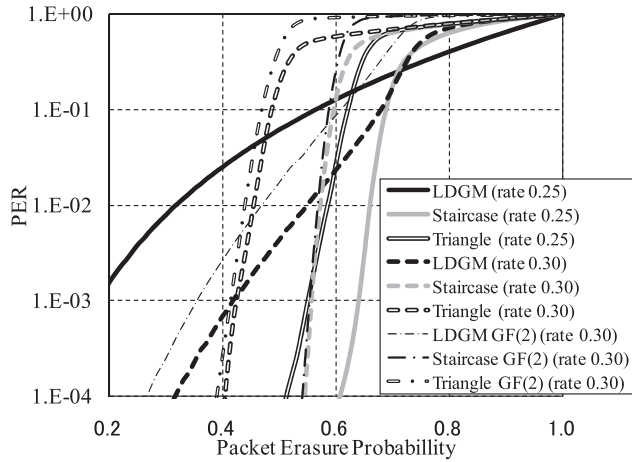
#### 5. Numerical Results

We evaluate the proposed coding system through computer simulations. The result of Fig. 8 shows that the data erasure



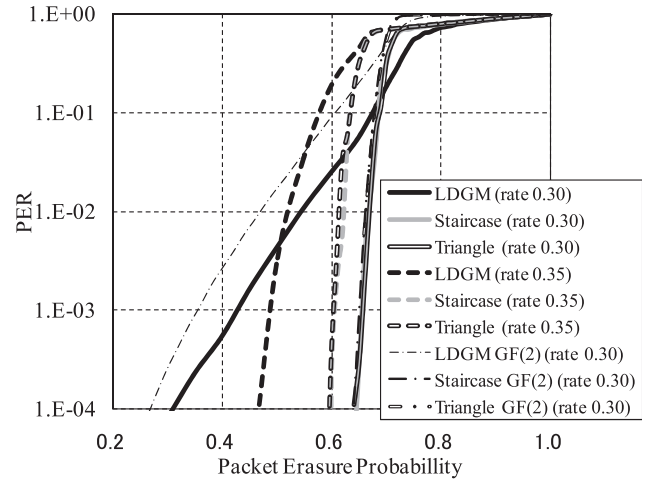
**Table 3** Simulation parameters for LDGM code comparison.

Channel	Random packet erasure		
Code	LDGM, LDGM Staircase, LDGM Triangle		
Galois field	$GF(2)$ , $GF(2^8)$		
Code length	$N=1020$		
Code rate	0.25	0.30	0.35
weight (j,k)	(3,1)	(7,3)	(13,7)
Decoding	Iterative decoding		
	Hybrid decoding		
Num. of trans. packets	$5 \times 10^7$		

**Fig. 13** PER comparison of LDGM, LDGM staircase, and LDGM triangle with iterative decoding.

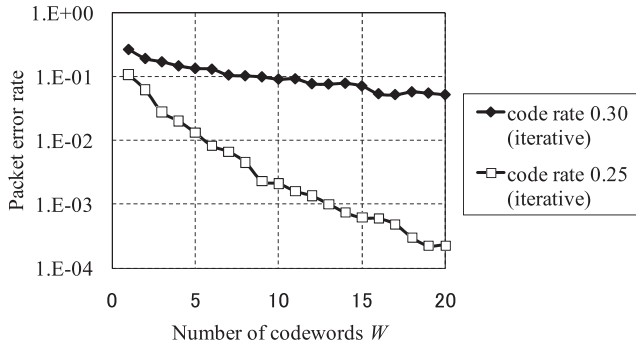
probability in four-state Markov channel is between 0.5 and 0.6 regardless of feedback. This means that 0.7 redundancy of the LDGM code is sufficient in four-state Markov channel. Therefore, we compose LDGM, LDGM Staircase, and LDGM Triangle codes with the coding rate of around 0.30. First, to confirm the capability of erasure, the packet error rate performances in random erasure channel are calculated and compared where the simulation parameters are listed in Table 3. In [16], it was described that an error-free transmission was obtained in LoS free-space laser communication. Thus, we assume LoS as error-free and NLoS as all erasure. One symbol consists of eight bits by the use of  $GF(2^8)$ . The results of Fig. 13 show that the LDGM Staircase code has the best performances and sufficiently recover the 0.5 symbol erasure with the iterative decoding at the rate of 0.25 and 0.30. Fig. 14 shows that the LDGM Staircase and Triangle codes with hybrid decoding have the best performances. Compared with the LDGM on  $GF(2)$ , the performance of  $GF(2^8)$  is slightly better because a byte-unit processing improves the packet recovery ability. Since the density of parity check matrix is lower in LDGM Staircase than LDGM Triangle, the decoding complexity can be lower in LDGM Staircase and we apply it in the system of Fig. 12.

We evaluate the PER performance on the four-state Markov channel to find a good code configuration for op-

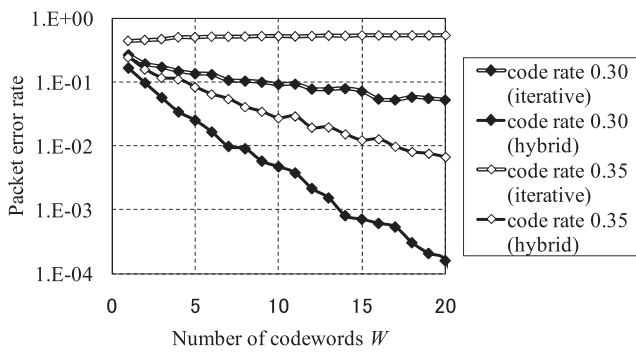
**Fig. 14** PER comparison of LDGM, LDGM staircase, and LDGM triangle with hybrid decoding.**Table 4** Simulation conditions of satellite-to-ground transmission.

Channel	4 state Markov		
Transition Probability	Pa1=0.27 Pb1=0.24 Pa2=0.06 Pb2=0.05		
State condition	LoS : No error NLoS : All Erasure		
Transmission speed	1[Mbps]		
Cycle of fluctuation of channel	every 50bit		
modulation	BPSK		
Code	LDGM Staircase		
Galois field	$GF(2^8)$		
Code length	$N=1020$		
Code rate	0.25	0.30	0.35
weight (j,k)	(3,1)	(7,3)	(13,7)
Decoding	Iterative decoding		
	Hybrid decoding		
Number of codeword $W$	1 to 20		
Interleaver	S random byte interleaver S=5		
Channel estimation	Perfect		
Number of transmitted packets	$1 \times 10^5$		

tical satellite-to-ground transmission. The simulation conditions are listed in Table 4. The PER performances with iterative decoding are shown in Fig. 15 and those with hybrid decoding are shown in Fig. 16. The channel erasure estimation in the receiver is assumed perfect. The bit error rate of BPSK is identical to binary 2-PPM (Manchester), i.e., the modulation performance is the same as OICETS experiments. We calculate the PER versus the number of codeword  $W$ , i.e. the interleaver size. If  $W$  is increased, the burst erasure is dispersed more and the channel is approaching to the random erasure channel, which can be effectively recovered by LDGM code. The drawback is the increase of decoding complexity. Therefore, a small  $W$  with good PER performance is desired. The results in Fig. 15 show that the performance with iterative decoding at the rate of 0.30 was



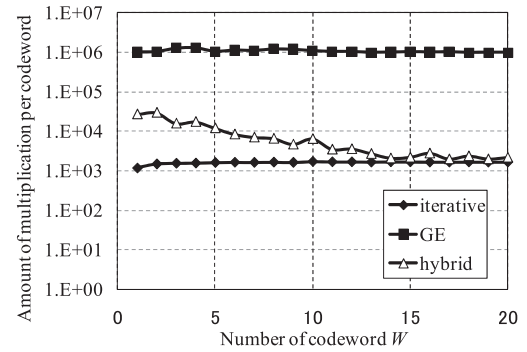
**Fig. 15** PER performance of LDGM staircase versus the number of codeword by using iterative decoding.



**Fig. 16** PER performance of LDGM staircase versus the number of codeword by using hybrid decoding.

not improved even with a larger  $W$ . This means that the erasure probability is almost 0.6 and the PER cannot be improved by the rate of 0.30 as shown in Fig. 15. Meanwhile, at the rate of 0.25 the PER is improved gradually with the increase of  $W$ . The PER of  $10^{-2}$ , recognized as acceptable error rate in general, is achieved at  $W = 6$ . Similarly, the results of Fig. 16 showed that the PER of  $10^{-2}$  is achieved at  $W = 7$  (code rate = 0.30) and  $W = 17$  (code rate = 0.35) with hybrid decoding. Furthermore, Fig. 16 showed that the performances of hybrid decoding are better than those of iterative decoding. Therefore, the frame size less than 48,960 bits (6120 symbols) of LDGM code with an interleaver is effective for 1 [Mbps] satellite-to-ground transmission. For higher speed transmission, this size will be increased proportionally.

Figure 17 shows the average amount of multiplication per codeword by using each decoding method in 4-state Markov model. The code rate is 0.25, and other conditions are the same as Table 4. The results show that GE decoding cannot achieve high-speed decoding since the average amount of multiplication using GE decoding is very large. Meanwhile, the difference between iterative decoding and hybrid decoding reduces as  $W$  grows, and it becomes almost the same over  $W = 13$ . Therefore, high-speed decoding whose average amount of multiplication is low is achieved by using iterative decoding or hybrid decoding.



**Fig. 17** Average amount of multiplication per codeword.

## 6. Conclusion

In this paper, we proposed an optical satellite-to-ground channel model based on a 4-state Markov model. A few number of states is added to take into account both short- and long- time fluctuation and it has been shown that the probability density distribution of burst erasure becomes identical to the OICETS experiment results. In addition, using this model we proposed an efficient channel coding scheme of LDGM Staircase code. Through numerical results we clarified that six, seven or seventeen concatenation of 8160-bit (1020-symbol) LDGM Staircase code at the rate of 0.25, 0.30 or 0.35 with interleaver achieved the PER of  $10^{-2}$ . These results confirm that the LDGM coding system can realize high-quality data transmission over laser satellite-to-ground links.

The results of this paper indicate that the high-quality transmission can be achieved by the design of appropriate channel model and suitable coding design for laser satellite communications. The use of higher-degree LDGM code is efficient without using the soft-decoding algorithm for the current terrestrial systems use.

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