4-4 Transmission Experiments on OICETS Repeater Mode for Verification of Channel Coding Effect

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In satellite-to-ground laser communication, the received optical power often decreases by atmospheric turbulance, beam pointing error, and tracking error, resulting in a transmission quality deterioration. To avoid this, cahnnel coding should be adopted in such laser communications. In this paper, we consider applying a low-density parity check (LDPC) code, one of the strong error correcting codes, for the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) laser communication. A suitable code in terms of field programmable gate array (FPGA) implementation is designed by computer simulation analysis and based on these results, the threemode realtime LDPC decoder is composed. Then, we carried out the demonstration experiment in which LDPC-encoded data were transmitted in uplink and downlink with the repeater mode of OICETS. As a result of its offline decoding analysis, we found that the channel coding effect was obtained in a limited way. Finally, from this result, we consider a better code design for the satellite-to-ground laser communication to improve the performance.

Keywords
OICETS repeater mode, Error correcting code, LDPC code, Transmission experiment

1 Introduction

In recent years, optical satellite communication has attracted attention as one of the systems that satisfies the demand for large capacity communication. Optical satellite communication can construct a large capacity network on a global scale, withstand disasters on the earth, and has high confidentiality because of a highly rectilinear property. However, free-space optical communication may be reportedly subjected to attenuation that is different from radio waves due to atmospheric turbulance in the transmission path at the time of long distance propagation in particular, resulting in deterioration of quality. In an experiment between the OICETS (Optical Inter-orbit Communications Engineering Test Satellite) and the ground held in 2006 [1], variations in the intensity of received optical signals have been clarified in both uplink and downlink except for loss of synchronization [2]. In order to achieve next generation optical satellite communication of more than 10 Gbps, an effective channel coding that can cope with variations is considered to be indispensable. In the reference [3], investigation is performed on various coding for the OICETS transmission path and a turbo code is found to be effective. Accordingly, in the present study, effective channel coding was designed in the OICETS experiment in fiscal 2008 based on this investigation and studied for the purpose of performing a demonstration experiment. Here, as a powerful channel coding method, a turbo code [4] and an LDPC (low-density parity check) code [5] were cited. There is no significant difference in characteristics between the two. However, since implementation is easy, there is a strong affinity with a packet structure, and change of design such as code length is easy, so we employ the LDPC code [6].

In this paper, an outline of the LDPC code is given in **2** along with the design of the

LDPC code that can be implemented on a transmission device and applied to the OICETS, and the results of a study by computer simulation are mentioned in **3**. In **4**, the influence of transmission error of an OICETS uplink is clarified. In **5**, a transmission system using the repeater mode of the OICETS is constructed. In **6**, the results of the demonstration experiment are described. In **7**, code design necessary for improving coding performance is considered. Finally, a summary is given in **8**.

2 LDPC coding and Sum-product decoding

An LDPC code is an error correction code that performs iterative decoding processing and is a linear block code defined by a significantly sparse parity check matrix. A combination of the LDPC code and Sum-product algorithm, its decoding method has an extremely high error correction capability which is superior to a turbo code when the code length is sufficiently long, having a performance closing in on the Shannon Limit. Further, when compared with the turbo code, the LDPC code has a smaller amount of decoding operation and can be easily expanded into various code rates and code lengths. Since the arrangement of the code is random, the effect of an interleaver is included in a codeword, achieving a high correction capability of burst errors. The LDPC code is classified into a Regular LDPC in which each row of the check matrix has a constant weight and an Irregular LDPC. The Irregular LDPC is known to have more excellent bit error correction capability than the Regular LDPC because of a favorable distribution of row weights and column weights in general. However, since the Irregular LDPC code is not randomly arranged, an error floor may be generated depending on the selection of the code length and the number of orders. The object of the present study is to implement the LDPC code of various settings to evaluate it by experiments. Accordingly, we will employ the Regular LDPC code by attaching great importance to easy construction.

Descriptions are given of the Sum-product decoding method, which is a typical decoding method of the LDPC code. The Sum-product decoding method is classified into the probability region Sum-product decoding method and logarithmic region Sum-product decoding method. In the present study, we employ the logarithmic region Sum-product decoding method because it is easy to handle for numerical calculations and suitable for hardware implementation. Its algorithm is described as follows.

The log likelihood ratio LLR is defined in the following equation when received through an additive white Gaussian noise (AWGN) channel.

$$\lambda_n = \ln\frac{P(r_n|x_n=0)}{P(r_n|x_n=1)} = \ln\frac{\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left\{\frac{-(r_n-1)^2}{2\sigma^2}\right\}}{\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left\{\frac{-(r_n+1)^2}{2\sigma^2}\right\}} \qquad (1)$$
$$= \frac{-(r_n-1)^2+(r_n+1)^2}{2\sigma^2} = \frac{2}{\sigma^2}r_n \quad (1 \le n \le N)$$

where, x is a binary transmission bit sequence of code length N at the time of BPSK modulation, r is the reception signal sequence, and σ^2 is the dispersion of noise. When the information length is K, the parity check matrix H becomes (N-K) rows and N columns. Corresponding to the parity check matrix, a Tanner graph can be configured like Fig. 1. The upper part of a Tanner graph is called a variable node, having the number of nodes equal to the number of columns N of the check matrix. The node n corresponds to the n-th

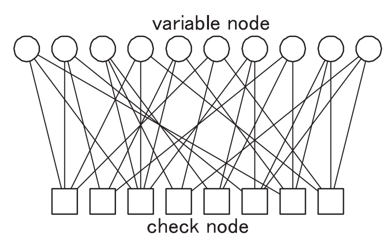

Fig.1 *Example of Tanner graph*

column. The lower part is called a check node, being equal to the number of rows (N-K). The node m corresponds to the m-th row. When an element of column m and row n of the parity check matrix is $H_{m,n}$, between the variable node n and the check node m, corresponding $H_{m,n} = 1$ are connected. Here, the LLR of the variable node is $u_{m,n}$ and the LLR of the check node is $v_{m,n}$. The $u_{m,n}$ is referred to as a prior LLR and the initial value is zero. Using (m, n) that satisfies $H_{m,n} = 1$ of each column, an external LLR $v_{m,n}$ is updated for all columns by the next formula.

$$v_{m,n} = \left\{ \prod_{n' \in N_m \backslash n} sign\left(\lambda_{n'} + u_{m,n'}\right) \right\} f \left\{ \sum_{n' \in N_m \backslash n} f\left(\left|\lambda_{n'} + u_{m,n'}\right|\right) \right\} \quad (2)$$

where, $sign$ (x) and $f(x)$ are defined by the next formulas, respectively.

$$sign(x) \equiv \begin{cases} 1, & x \geq 0 \\ -1, & x < 0 \end{cases} \quad (3)$$

$$f(x) = \ln \frac{e^x + 1}{e^x - 1} = \ln\left(\tanh\left(\frac{x}{2}\right)\right) \quad (4)$$

A function f defined by formula (4) is called Gallager's f function. Next, using the external LLR $v_{m,n}$ updated by formula (2), a prior LLR$u_{m,n}$ is updated for all columns by the next formula.

$$u_{m,n} = \sum_{m' = M_n \backslash m} v_{m,n} \quad (5)$$

Then, as for $n \in \{1, \cdots, N\}$, the following formula is calculated and a temporary presumption $\hat{c} = (\hat{c}_1, \hat{c}_2, \cdots \hat{c}_N)$ is calculated.

$$\hat{c}_n = \begin{cases} 0, & if \quad sign\left(\lambda_n + \sum_{m' \in M_n} v_{m,n}\right) = 1 \\ 1, & if \quad sign\left(\lambda_n + \sum_{m' \in M_n} v_{m,n}\right) = -1 \end{cases} \quad (6)$$

When the temporary presumption obtained here satisfies the following codeword condition for a linear code,

$$\hat{\mathbf{c}}\mathbf{H}^T = \mathbf{0} \quad (7)$$

it is output as a decoding result and iterative processing is terminated. When not satisfied, the processing is repeated. When formula (7) is not satisfied even at the maximum repetition number, the presumption at that time is output as decoding results.

In the present study, since high error correction capability is obtained in optical satellite communication and it is a linear code whose implementation is relatively easy, LDPC coding using the Sum-product algorithm is applied. In this case, although the quantization of variables of the Sum-product algorithm is necessary for implementation, this results in a trade-off between performance, required memory, and the amount of operation. These relations are clarified by simulation as follows.

3 Influence of quantization for FPGA implementation and code design suitable for implementation

Since Sum-product decoding of the LDPC code employs a soft value like in **2**, the operation of a decimal number is necessary. In a computer simulation, although the LLR used for decoding calculation is usually calculated as a floating decimal point variable, quantization is required due to the restriction in memory length of the variable at the time of implementation. In order to check the influence of deterioration by quantization, the number of bits required for quantization is evaluated by computer simulation [7]. The parameters subjected to quantization in a decoder are threefold: a communication path value λc from formula (1); a logarithmic prior value $u_{m,n}$ from formula (5); and a logarithmic external value $v_{m,n}$ from formula (2), which are primary variables for deriving the LLR. Since a post LLR from formula (6) is calculated from the sum of these, no quantization operation is performed. At first, the distribution of the value of these parameters is checked when no quantization is performed. Figure 2 shows the distribution of the absolute values of λc, $u_{m,n}$, $v_{m,n}$, and post LLR when the code length is 1,032, rate 0.502, Eb/N0 = 2 dB, with the maximum value x of the Gallager function from formula (4) being 10, and iterative decoding operation being the seventh. In this example, the distribution of λc is found to reach $x = 10$ and that of $u_{m,n}$ and $v_{m,n}$ is in the vicinity of $2x = 20$. Based on these results, simulation of quantization is performed. For λc, $u_{m,n}$, and $v_{m,n}$, the number of bits of quantization is n and the maximum value is m. Then, the number of values becomes 2^n and the extent becomes $-m$ to m. Figure 3 shows the bit error rate (BER) characteristics when m for each λc, $u_{m,n}$, and $v_{m,n}$ is 8, the maximum iteration number of decoding 40, code length 1,032, and rate 0.502. As a result, almost the same characteristics as in the case of no quantization are obtained when the number of bits of quantization are 8 bits or more. When $m = 8$ and $n = 8$, the difference per step of quantization is $2\ m/2^n = 0.0625$. Next, the BER characteristics are calculated when $n = 8$ bits and the value of m is varied. As shown in Fig. 4, no significant difference is observed in the total. It is found that when m is 8 or more, there is no problem.

Finally, the characteristics when the extent

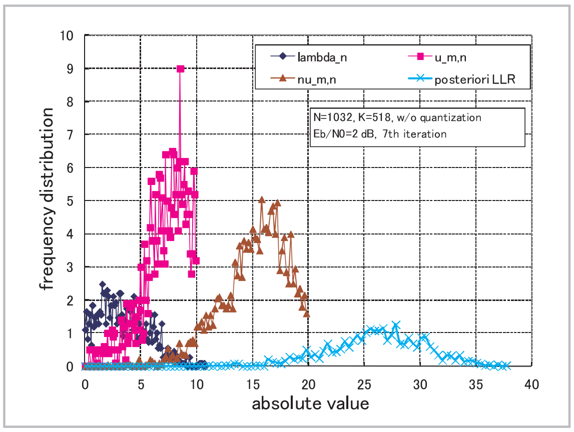

Fig.2 Distribution of λ c, $u_{m,n}$, and $v_{m,n}$, and post LLR in decoding process

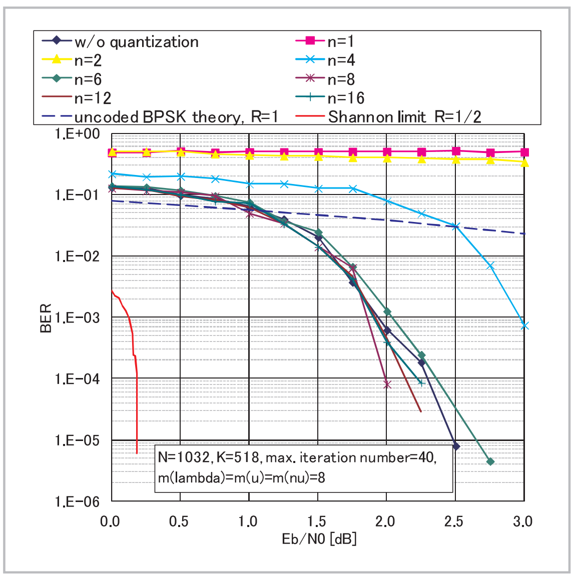

Fig.3 BER characteristics for number of quantization bits

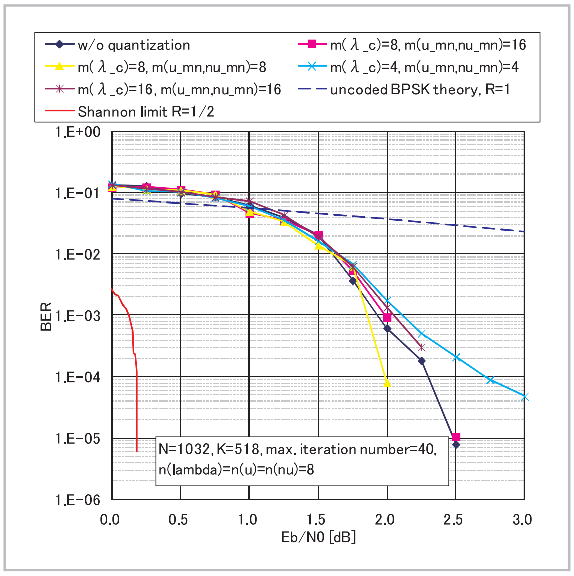

Fig.4 BER characteristics for extent m of parameters

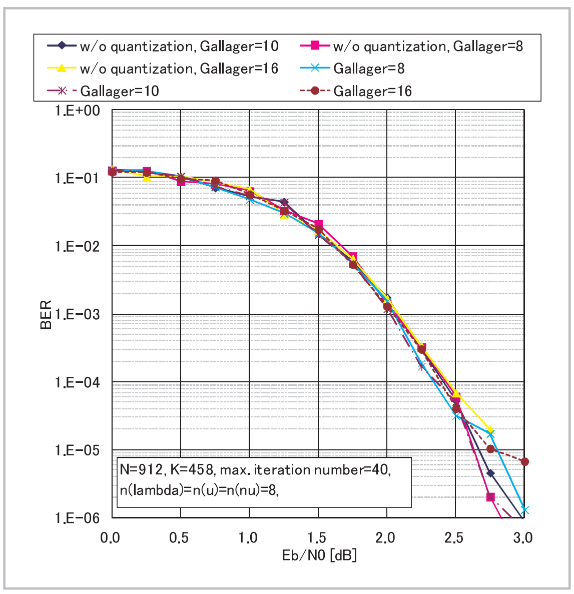

Fig.5 BER characteristics for quantization of (912,458) LDPC code and extent of Gallager function

of the Gallager function is made to be a power-of-two and the characteristics for the quantization of (912,458) code to be described in **5** are checked. Figure 5 shows the characteristics in an AWGN channel when a modulation method is BPSK, the number of bits of quantization is n = 8 for each communication path value λc, logarithmic prior value $u_{m,n}$, and logarithmic external value $v_{m,n}$, maximum value m = 8, and maximum iteration number of decoding 40 times. As shown in the figure, each BER characteristics is found to be almost the same. No change is observed when the extent of the Gallager function is large on some level. Thus, the number of bits of quantization is n = 8, maximum value m = 8, and the extent of the Gallager function may be 8.

Accordingly, as a result of the present simulation, decoding with almost no deterioration is found to be possible when the number of bits of quantization is 8, the extent of the parameter –8 to 8, and the upper limit value of the Gallager function being 8 in the LDPC decoding.

4 Influence of uplink error in OICETS loop-back link

In a loop-back link of communication equipment between the optical satellites (LUCE: Laser Utilizing Communication Equipment) of OICETS, an uplink signal is once subjected to a hard decision in satellite onboard equipment. Then, its influence is studied by simulation. In the case of LDPC code transmission, the influence of a hard decision in the middle of a communication path is considered to be as follows. When a wrong bit is sent back and received at the Earth station at the time of a hard decision of the uplink, the sign of the communication path value λc of the received signal is inverted compared with a normal decision. Simulations are performed such that with a bit error rate at the time of uplink, a hard decision is a parameter, the horizontal axis is Eb/N0 dB of the downlink, and the vertical axis is the BER characteristics of the entire loop-back communication. Figure 6 shows the results when the modulation method is BPSK, the number of bits of quantization n = 8, maximum value m = 8, the maximum number of iterations of decoding is 40, and the downlink is an AWGN channel. From the figure, almost the same BER characteristics as at the time of no error in the uplink is found to be obtained by the LDPC error correction capability when the bit error rate of the uplink is 10^{-3} or less. When judging from these results, the required quality of the uplink can be said to be BER = 10^{-3}. However, in actual optical communication, since a burst error frequently occurs, countermeasures will be necessary.

5 Determination of mode of LDPC code to be applied to OICETS experiment and real time receiver

From **3**, the characteristics at the time of quantization of 8 bits is found to be almost the same as that of no quantization when implementing LDPC. From reference [6], when utilizing the resources of the FPGA (Field Programmable Gate Array) Xilinx XC4FX100F1152-11 used for the equipment to a maximum extent, the upper limit of the

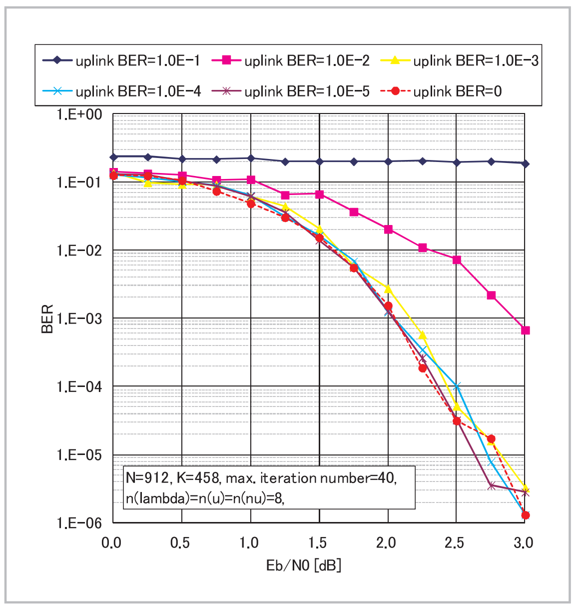

Fig.6 *BER characteristics of loop-back link considering bit error of uplink*

code length becomes 912 bits and the code rate and the number of repetitions are found to have not much influence on a use rate of the resource. In the experiment, three settings of LDPC transmissions, whose difference in performance is clear, are defined so that the difference in the setting of the code should not be hidden by changes in characteristics and performance degradation of the propagation path and equipment. At first, R ≒ 0.5 (912,458) #40 is used for code mode 1, for which maximum performance can be expected in the extent of a given resource. Here, # denotes the number of maximum decoding iterations, all being 40 regardless of the mode. Next, as a code length and code rate for which the observation of differences in characteristics can be relatively expected, R ≒ 0.5 (258,131) having the same code rate and shorter code length is made to be mode 2. Further, R≒0.8 (252,206) having almost the same code length as mode 2 and higher code rate is made to be mode 3. Figure 7 shows the BER characteristics in the AWGN channel of these three modes. The figure shows that at BER = 10^{-3}, which is the required performance of the uplink, a difference of approximately 0.7 [dB] between mode 1 and mode 2 and that of approximately 1 [dB] between mode 2 and mode 3 are found to be obtained. Consequently, three modes shown in Table 1 are decided to be implemented in FPGA because it is a mode that can obtain a difference in performance even when being hidden by changes in the characteristics of the equipment and performance degradation. Figure 8 shows an appearance diagram of a receiving circuit. The receiving circuit is composed of a single board and an A/D converter (ADC) and two FPGAs are mounted thereon. An input signal is subjected to sampling with a frequency of maximum 6 GHz by the ADC to be converted into 8-bit digital data. Thereafter, in the FPGA (XC5VSX95) at the prior stage, PPM demodulation and frame synchronization processing are performed to be input into the FPGA (XC4FX100) at the post stage. Figure 9 shows a block diagram of LDPC demodulation processing part by XC4FX100 at the post

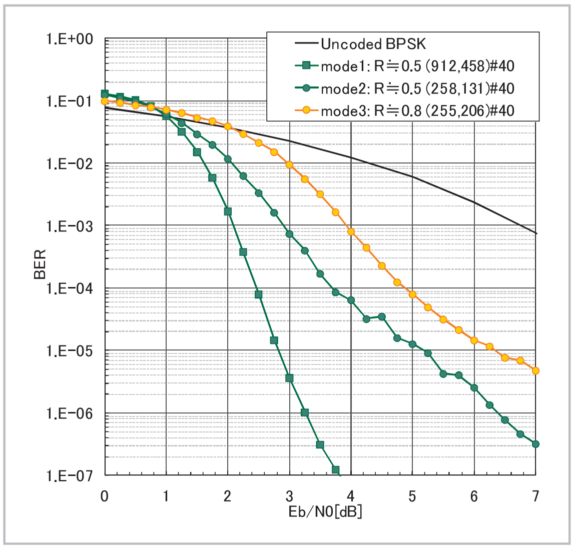

Fig.7 BER characteristics of 3 mode used for OICETS experiment in AWGN channel

Table 1 3mode (LDPC code for FPGA)

	Code late R	Code length M	Info bit N	Num of iterations
mode1	about 0.5	912	458	40
mode2	about 0.5	258	131	40
mode3	about 0.8	252	206	40

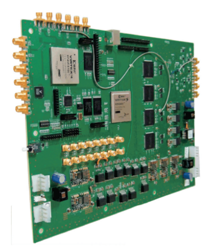

Fig.8 Appearance of real-time receiving circuit

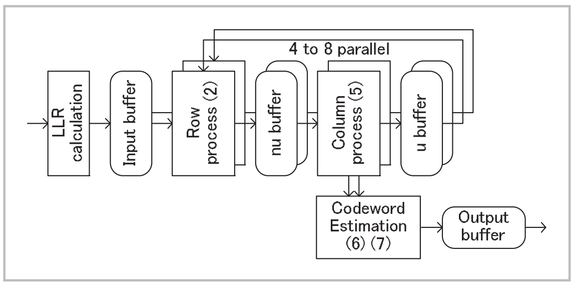

Fig.9 Block diagram of LDPC signal processing by FPGA

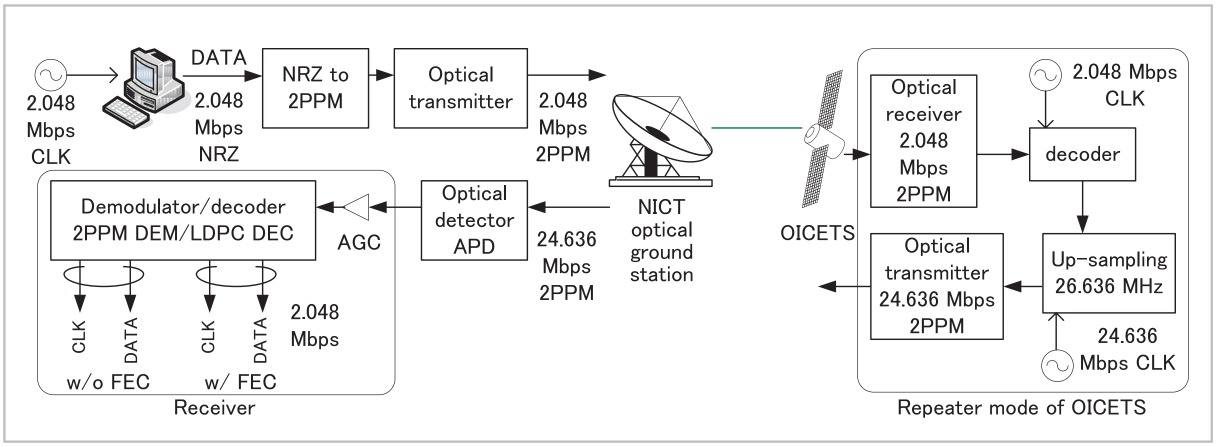

Fig.10 *Experiment system of LDPC code transmission using OICETS repeater mode*

stage. The numbers in Fig. 9 denote the number of formulas in **2**. This FPGA is driven by about 150 MHz and subjected to Sum-product decoding processing by each formula according to **2** in parallel. Then, the data after error correction is output.

6 Outline of experiment system and demonstration test

The transmission experiment with the OICETS is performed using the designed LDPC code. Figure 10 shows an experiment system. A transceiver is installed at an optical earth station at NICT Koganei. On the transmitting side, LDPC code data input off-line is subjected to 2-PPM demodulation and transmitted. Although the OICETS has a plurality of communication modes, a repeater mode is employed in the present experiment, in which a binary PPM signal of upstream 2.048 Mbps received from the ground station is subjected to hard decision demodulation, and loop-back transmission as downstream data as shown in Fig. 10. However, since specifications such as data rates are different for upstream and downstream, the satellite up-samples NRZ data obtained by demodulating upstream data with 24.636 MHz as the basic clock rate for downstream, and the data is transmitted as a binary PPM signal of 24.636 Mbps downstream. The receiver at the ground station performs modulation and demodulation processing of a down-

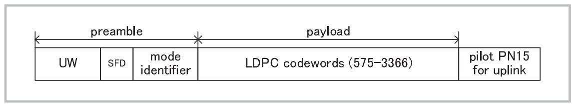

Fig.11 *Configuration of transmission frame*

stream signal on a real-time basis. A decoder outputs data after LDPC decoding (w/FEC in Fig. 10) and data before LDPC decoding and after demodulation (w/o FEC in Fig. 10) simultaneously as a result of decoding. This allows the effect of error correction of the LDCP to check on a real-time basis.

Figure 11 shows the configuration of a transmission frame used in the experiment. All the preamble parts are composed of a 9-stage PN series. At first, as a unique word (UW) for acquiring synchronization, five PN series are continued and a start frame delimiter (SFD) is inserted. Then, using two PN series, the mode number of the LDPC codeword in the payload is notified (mode identifier). In the payload part, a different number of LDPC codewords are arranged for each mode. In order to make a single experimental frame length coincide, 575, 1987, and 3366 codewords are inserted in mode 1 to 3, respectively. Since the LUCE has a function to measure the BER for the 15-stage PN series, a pilot PN series for measuring the uplink BER is inserted at the subsequent stage of 16 payloads. This PN series can be used for measuring the BER off-line at the receiving side on the ground. These are transmitted as a single experimental frame. For transmission by a transmitter, a transmission frame is prepared in advance on-line using a PC. After a communication link has been established between the OICETS and the ground station, the prepared transmission frame is transmitted, a returned signal at the repeater mode is received, and data output from the external output is input into a storage device. Performance evaluation of the LDPC code is conducted by analyzing data in the storage device offline.

7 Experiment results

A communication experiment between the OICETS and the ground has to be performed during the night to prevent the influence of background light. Since a low orbit satellite is used, the experiment allowable time becomes less than 10 minutes per one experiment path. Since various experiment items are scheduled, the present code transmission experiment can be performed only several times. In such a limited path, LDPC frame transmitting/receiving experiment has succeeded three times and the frame in each mode has been stored in the receiver. However, uplink and downlink BER observation using a 15-stage PN series cannot be performed. Regarding mode 2, measurement has been performed but significant decoding results could not be obtained. The results of analysis are shown as follows.

Figure 12 shows the BER characteristics obtained by analyzing output from the receiver on a real-time basis at the time of mode 1 transmission conducted on December 18, 2008. Figure 12(a) and 12(b) are uncoded and LDPC decoding, respectively. The vertical axis is the number of transmission bits, that is, a time axis. The vertical axis is the BER per experiment frame. The detection unit for BER is (the number of bits observed in mode 1: 912) × (the number of codewords of mode 1 in one experiment frame: 575), corresponding to 0.26 seconds. In the first half of Fig. 12(a) and 12(b), the BER is almost 0.5 because synchronization acquisition is not obtained. The second half after acquiring synchronization varies

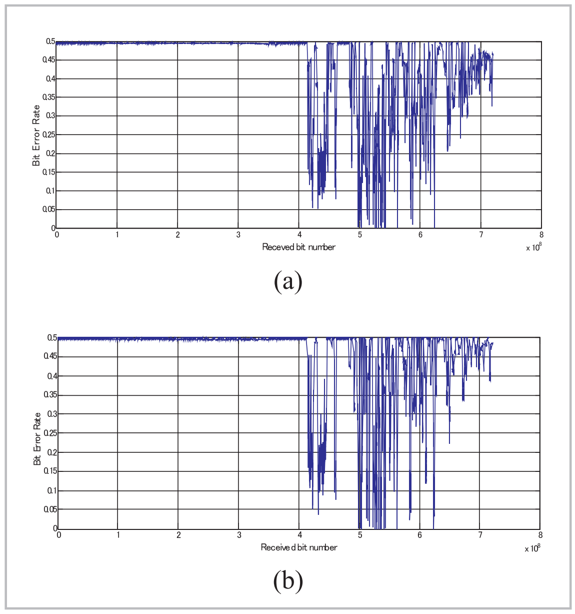

Fig.12 *Characteristics of received BER in mode 1*

(a) Received data prior to LDPC decoding
(b) Received data after LDPC decoding

according to the conditions of the transmission path and Fig. 12(a) and 12(b) showing almost the same BER transition. The number of times of BER = 0 by coding increases from once in Fig. 12(a) to six times in Fig. 12(b). This is caused by the effect of the LDPC code, and the effect of coding is verified. However, as shown in Fig. 12, the BER changes a lot, revealing that the effect of coding is limited. This is caused because a fluctuation period of the transmission path of an optical loop-back link is longer than the time after LDPC 1 coding.

Next, Figure 13 shows BER characteristics at the time of mode 3 transmission conducted on January 15, 2009. The vertical and horizontal axes are the same as those in Fig. 10. The detection unit for BER is (the number of bits observed in mode 3: 255) × (the number of codewords of mode 3 in one experiment frame: 3366), corresponding to 0.42 seconds. When comparing the effect of LDPC decoding in Fig. 13(a) and 13(b), although a similar transition is observed by the figure, a little degradation is found. That is, while the minimum BER in the figure is 6.3×10^{-3} in Fig. 13(a), and it is 1.6×10^{-2} in Fig. 13(b). Error correction seems to be not effectively operated

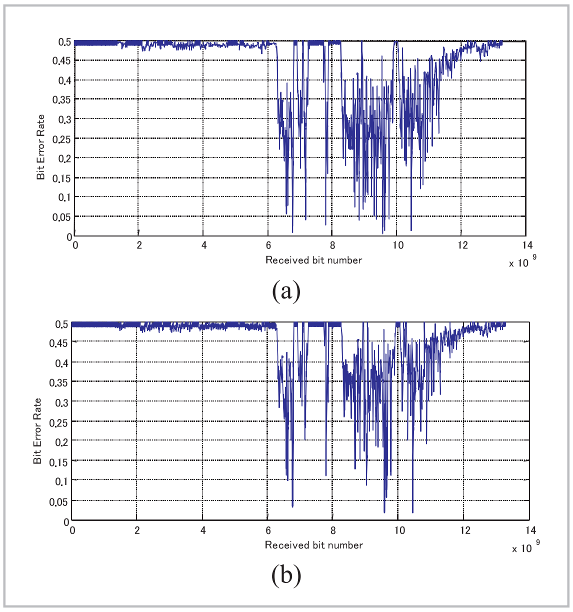

Fig.13 *Characteristics of received BER in mode 3*

(a) Received data prior to LDPC decoding
(b) Received data after LDPC decoding

because of a high BER prior to LDPC decoding on average in the BER detection unit due to the high code rate of mode 3. Accordingly, when setting a short code length and a high code rate, it is found that the scope of application of conditions of the receiving side to be assumed has to be studied.

From the above, although being restrictive, the effect of LDPC coding in mode 1 is verified by experiment. Effective extension of the code length, and a strong error correction effect, that is, low code rate are confirmed to be necessary, which are problems for the future.

8 Study on code configuration for improving characteristics

In order to improve the effect of error correction codes in satellite-to-ground optical communications, it is necessary, like in **7**, to extend effective codeword lengths and to improve error correction capability. However, when using soft decoding as mentioned in **5**, since the scale of the circuit becomes large at the time of implementing a decoder, there is a limit in extending the code length. On the other hand, in references [8] and [9], descriptions are given that for error correction codes in free-space optical transmission, modeling of an erasure channel and decoding using a hard value are effective. An erasure channel is a binary model, in which a threshold value of received power for which the receiving side becomes error free is provided and reception is treated as normal when exceeding the threshold, and as disappearance when falling below the threshold. In this case, the decoder doesn't need to calculate soft values such as LLR, allowing the amount of calculation to be reduced. Accordingly, in the configuration of satellite-to-ground optical communication having high error correction code effects, to treat a communication path as an erasure channel, to reduce the amount of calculation by performing decoding as a disappearance code, and to extend an effective code length using an interleaver are considered to be effective. Based on the above study we have shown that to use a long LDGM (low-density generator matrix), which is a kind of LDPC code, to widely extend the effective code length via an interleaver, to treat the communication path as an erasure channel, and to perform linear decoding using a hard value at the receiving side are effective for satellite-to-ground optical communication [10]. At present, we are investigating the demonstration of spatial optical transmission based on the study.

9 Summary

In the present study, we have studied for the purpose of demonstrating the effect of an error correction code between the satellite and the ground using an OICETS repeater mode. While focusing on the LDPC code as a strong error correction code, computational simulations have revealed that by performing quantization with 8 bits at the time of implementing a transceiver FPGA, the same characteristics can be obtained as at the time of performing no quantization, and the required quality at the time of being returned in the uplink is BER = 10^{-3}. While considering the use rate of resources at the time of implementation, three modes of the LDPC code used for the experiment are designed. In order to obtain a significant difference in code performance, the code length and the code rate are made to be relatively different and are selected such that R≒0.5 (912,458) for mode 1, R≒0.5 (258,131) for mode 2, and R≒0.8 (252,206) for mode 3. Then, we succeeded in code transmission in OICETS repeater mode and verified the effect of coding of mode 1, though limited. Since a long effective code length via an interleaver is revealed to be necessary as a problem in the future, we are going to design a code based on hard decision linear processing in optical satellite communication in the future.

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