

# Multi-Rate and Multi-BEP Transmission Scheme Using Adaptive Overlapping Pulse-Position Modulator and Power Controller in Optical CDMA Systems

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**Abstract:** We propose a multi-rate and multi-BEP transmission scheme using adaptive overlapping pulse-position modulator (OPPM) and optical power controller in optical code division multiple access (CDMA) networks. The proposed system achieves the multi-rate and multi-BEP transmission by accommodating users with different values of OPPM parameter and transmitted power in the same network. The proposed scheme has advantages that the system is not required to change the code length and number of weight depending on the required bit rate of a user and the difference of bit rates does not have so much effect on the bit error probabilities (BEPs). Moreover, the difference of transmitted powers does not cause the change of bit rate. We analyze the BEPs of the four multimedia service classes corresponding to the combinations of high/low-rates and low/high-BEPs and show that the proposed scheme can easily achieve distinct differentiation of the service classes with the simple system configuration.

**Index Terms:** Adaptive overlapping pulse-position modulator (OPPM), multi-BEP, multi-rate, optical code division multiple access (CDMA), optical hard limiter, power controller.

## I. INTRODUCTION

In recent years, optical code division multiple access (CDMA) systems have been widely investigated in the area of high-speed optical networks [1]–[16]. The major advantage of the optical CDMA systems is the fact that each user can access the network asynchronously and simultaneously without strict wavelength control and timing synchronization which are needed in the case of wavelength division multiple access (WDMA) and time division multiple access (TDMA) [1]–[8]. Based on the ability for effective utilization of the vast amount of bandwidth, the optical CDMA systems have received much attention in optical local area networks (LANs) or access networks in which the nature of traffic tends to have burst property [1], [7]. The optical CDMA system assigns a code sequence to each user, and on-off-keying (OOK) and  $M$ -ary pulse-position modulation (PPM) are major modulation schemes [1]–[5]. The PPM is preferable to the OOK in terms of power-efficient. In the PPM, the length of code sequence is defined as a “PPM slot.” A pulse is transmitted in one slot out of  $M$  PPM slots defined as a “PPM frame” to represent data which includes  $\log_2 M$  bits.

A time-encoding is a major encoding scheme in the optical CDMA systems [1]–[8]. In the time-encoding scheme, a PPM

slot is divided into some chips of which the number corresponds to the code length of a code sequence. The chip duration corresponds to the time-width of a transmitted pulse. In the transmitter, an induced optical pulse is divided and embedded into the weighted (1's) chip positions of the user's signature sequence by using optical splitter and tapped delay lines [2]. In other words, time-spreading method is applied for the encoding. In the receiver, the optical pulses in all weighted positions are collected by an optical correlator consisting of optical delay lines in order to generate a peak value. Besides the time-encoding scheme, the coherent spectral-phase encoding scheme [14], the frequency hopping scheme [16], and the incoherent time/wavelength two dimension encoding scheme [12], [13] have been considered as an encoding scheme in the research area of optical CDMA systems. In the coherent spectral-phase encoding scheme, a pseudo-random bipolar code sequence is assigned to each user, and the temporal shape of transmitted pulse for a given user is determined by encoding phases in the transmitted spectrum according to the assigned code sequence. The coherent spectral-phase encoding scheme can achieve higher bit-rate than the time-encoding scheme, but optical phase control causes the complexity of the system construction. On the other hand, in the frequency hopping scheme, an encoder slices the spectrum of an induced pulse and transmits a train of pulses in which the frequencies are hopping in time domain. The optical CDMA system with the frequency-hopping achieves a good correlation property among code sequences, but the maximum number of users is limited by the number of wavelength while not limited in the time-encoding scheme. The incoherent time/wavelength two dimension encoding extends the encoding to wavelength domain as well as time domain. In this study, we focus on the 1-D time-encoding as a simple encoding scheme.

Generally, optical CDMA systems suffer from multiple access interference (MAI) originating from other simultaneous users [1]–[13]. As the number of simultaneous users increases, the bit error probability (BEP) degrades because the effect of MAI increases. To mitigate the effect of MAI compared to the PPM-CDMA system,  $M$ -ary overlapping PPM (OPPM) has been used [9]. The OPPM is considered as a generalization to the PPM where overlapping is allowed between pulse positions and achieves more mitigation of MAI, which results in more improvement of BEP than the PPM. In addition, an optical hard limiter (OHL) has been used in front of the optical correlator [2], [8], [10], [12]. The OHL clips at a certain defined signal intensity which is the threshold value of OHL. If the incoming intensity is equal to or higher than the threshold value, the output is one (presence of pulse); otherwise, it is zero (absence of

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pulse). The threshold level of the OHL is set to the intensity of an optical pulse distributed in each weighted position. Using the OHL, the effect of MAI in each weighted position is up to only one pulse, which is more mitigated in comparison with the systems without the OHL.

The single-rate and single-BEP optical CDMA systems as described in [1]–[8] can accommodate only fixed rate and QoS (i.e., BEP). However, since we can expect that future optical networks include data traffic with multimedia services (e.g., text, image, audio, and video), the single-rate and single-BEP (power) are not suitable for the networks. Therefore, we are required to evaluate the optical CDMA system which achieves multi-rate and multi-BEP. Conventionally, the multimedia transmission schemes in which each user can transmit information data with various “bit rate” and “BEP” have received much attention in the research area of optical CDMA networks [17]–[24]. In TDMA or WDMA where QoS is usually handled in the higher levels such as the data link or network layer, a user needing more bandwidth can be allocated more time slots in TDMA or wavelength channels in WDMA. However, these schemes waste bandwidth when the traffic has burst property. On the other hand, optical CDMA has the advantage of providing differentiated service at the physical layer [7], [25]. In [17], parallel mapping method is employed to achieve various bit rates, in which the multiple codes in proportion to the bit rate must be assigned to each user. However, the number of users (not only the number of high-rate users, but also the number of low-rate users) are limited due to the total number of codes and the multiple optical encoders/decoders are required. In addition, the higher-rate users exhibit very low performance compared to the lower-rate users due to the large effect of MAI. In [18]–[22], various bit rates (multi-rates) among the users are achieved by changing the code length or the number of weight (i.e., the code sequence) for multi-rate optical CDMA networks. Generally, a long code length is assigned to each user with low-rate and a short one is assigned to each user with high-rate. Their schemes require multiple optical encoders/decoders or an optical variable encoder/decoder which can change the code sequence flexibly in optical domain. The code reconfiguration is required when a user changes the destination. In the case, in practice, the encoder/decoder are reconfigured at the same code-length and same number of weights. The “optical” processing of code reconfiguration is rather difficult. Also, when the system changes the code-length and number of weights, it needs to change the detection timing in the demodulator and number of tapped delay line, respectively. It requires more complicated processing in the receiver, and the implementation is rather difficult. Recently, multimedia services such as voice-over-IP (VoIP), video telephony, gaming, and e-commerce have been rapidly developed [25]–[27]. Thus, we can expect that multimedia services in which any kinds of traffic (i.e., video/audio and data) are simultaneously included increase drastically in future optical networks. Therefore, it is probable that traffic from a single user includes packets with several kinds of service classes in a short period. This means that the service class might be changed frequently even if a user sends data to the same destination. The conventional multimedia scheme in which the code-length and the number of weights change depending on the ser-

vice class causes the increase of complexity and the implementation is rather difficult. In addition, the several service requirements for bit rate and BEP cannot be easily guaranteed because the BEP significantly depends on the bit rate in the conventional multi-rate schemes. Actually, in the conventional multi-rate schemes, only two service classes (e.g., “high-rate and high-BEP” and “low-rate and low-BEP”) have been considered and analyzed [18]–[20]. Meanwhile, we must consider the multimedia scheme which changes the chip-rate depending on the service class. However, changing the chip-rate has a serious issue that the time-width of a pulse needs to be changed depending on the service class, which causes the increase of complexity in the laser-diode. In [23], multicode scheme has been proposed to achieve multi-rate. This scheme changes the number of transmitted pulses per frame depending on the required bit-rate of the user. This means that the code sequence does not need to be changed depending on the required bit-rate of the user, which results in simple system configuration. However, the number of available service classes for multi-rate is limited to the minimum interval between the weighted (1's) positions of the code. The future optical networks must guarantee more service classes for the variety of multimedia services. Therefore, it is essential to combine a new multi-rate scheme with the multicode scheme. Meanwhile, in [24], optical power controller is employed for various BEPs. This scheme is effective because the difference of transmitted powers has no effect on the bit-rate, which means that it can control the BEP independent of the bit rate. Thus, multimedia optical CDMA networks are required to handle multimedia (i.e., multi-rate and multi-BEP) service requirements more flexibly without changing the code sequence according to the service class of the user.

In this paper, first, we propose a multi-rate transmission scheme by using an adaptive OPPM in optical CDMA networks. Since the bit-rate varies depending on the number of slots  $M$  in the optical OPPM-CDMA systems at the same bandwidth, the proposed scheme can achieve the multi-rate transmission by accommodating users with different values of  $M$  in the same network. The proposed adaptive OPPM has an advantage that it is not required to change the code sequence depending on the required bit-rate of the user, and the bit-rate can be easily changed in the electronic domain while the conventional multi-rate schemes (in [18]–[20]) require to change the code sequence flexibly in the optical domain. This means that the proposed system can maintain the simplicity of the optical encoder/decoder which one user employs only one code sequence independent of the user's required bit-rate as in the single-rate optical CDMA systems. Moreover, the proposed adaptive OPPM has another advantage that the difference of bit-rates does not have so much effect on the BEP. Thus, we expect that the combining with the multi-BEP system achieves a larger number of service classes. We also apply an optical power controller to achieve multi-BEP in the optical multi-rate CDMA networks using the adaptive OPPM. Since the BEP depends on the transmitted power, a multi-BEP transmission can be achieved by accommodating users with different transmitted powers in the same network. The power controller requires only power attenuator and the difference of the power does not cause the change of the bit rate. In addition, we employ an OHL to eliminate more MAI

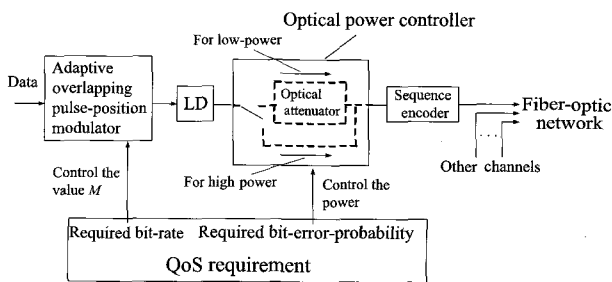


Fig. 1. The block diagram of the transmitter in the proposed system.

with lower power when the desired user transmits optical pulses with high power. Thus, the proposed scheme using the adaptive OPPM and power controller can easily achieve a large number of multimedia service differentiation with simple system configuration by using the combination of value  $M$  and optical transmitted power. In this paper, we divide the multimedia service into four classes that are the class A (high-rate and low-BEP), B (high-rate and high-BEP), C (low-rate and low-BEP), and D (low-rate and high-BEP) and analyze the BEPs of the four service classes. The adaptive OPPM and power control can be also applied to the coherent spectral-phase encoding, the frequency hopping and the incoherent time/wavelength two dimension encoding schemes because their encoding schemes can perform overlapping among pulses (or code sequences) and power controls. However, in this study, we focus on only time-encoding as a representative encoding scheme and clarify the advantage of the proposed schemes which can achieve the distinct differentiation of the QoS requirements. We show that the proposed scheme can achieve distinct differentiation of the four service classes without changing the code sequence depending on the service class of the user.

## II. PROPOSED SYSTEM

Fig. 1 shows the block diagram of the transmitter in the proposed system. In the transmitter, the adaptive OPPM selects the value of  $M$  corresponding to the required bit rate in electronic domain and modulates the information data. An optical pulse is induced in the first chip time of the corresponding slot by the laser diode, and is sent to the optical power controller. In the optical power controller, the optical intensity becomes low by the optical attenuator only when the information data corresponds to the high-BEP service. Next, the sequence encoder divides the pulse, embeds the divided pulses into the weighted positions of the user, and transmits the pulse sequences to the fiber-optic networks. Here, we employ optical orthogonal code (OOC), whose out-of-phase autocorrelation and maximum cross-correlation value are bounded by one, as a set of code sequences [6]. We assume that each user is assigned a unique code of OOC whose code length and number of weights are " $L$ " and " $\omega$ ," respectively. Fig. 2 shows the block diagram of the receiver in the proposed system. At the receiver side, the received optical pulses are sent to the OHL and the OHL clips at a certain defined signal intensity which is the threshold value of the OHL. If the incoming intensity is equal to or higher than the threshold value, the output is one (presence of pulse); otherwise, it is zero (ab-

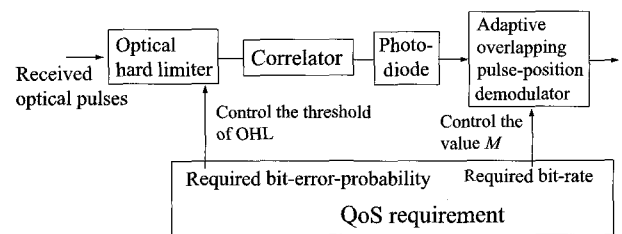


Fig. 2. The block diagram of the receiver in the proposed system.

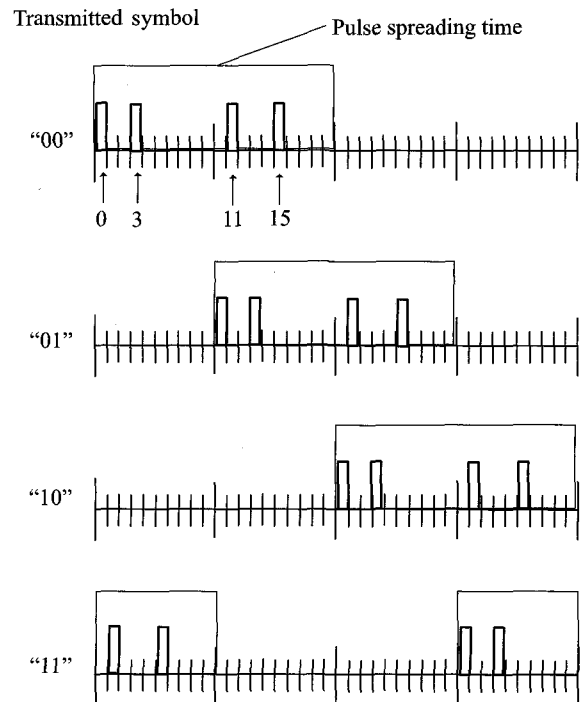


Fig. 3. An example of modulation in OPPM-CDMA system ( $M = 4$ ,  $\gamma = 2$ ).

sence of pulse). The threshold level of the OHL is set to the intensity of an optical pulse with the low-power or the high-power according to the service class of the user (i.e., the high-BEP or the low-BEP). Since the OHL with the low-level threshold clips at the low intensity independent of the intensity of the incoming pulse, it has the same ability as the OHL equipped in the single-rate optical CDMA systems [2]. On the other hand, since the OHL with high-level threshold is easier to eliminate the MAI with the low-power, the users with the high-power achieve better BEPs than the users with the low-power. After the OHL, the correlator collects the received optical pulses in the weighted positions into the same time position, and the photo-diode converts the optical signal to the electronic signal. At last, the adaptive overlapping pulse-position demodulator recovers the received bit sequence. The demodulator applies the maximum-value detection [9]. Fig. 3 shows an example of modulation in the single-rate OPPM-CDMA system. The number of PPM slots  $M = 4$ , and the number of PPM slots in the pulse spreading time (i.e., an index of overlap [9])  $\gamma = 2$  (note that the case of  $\gamma = 1$  corresponds to the PPM-CDMA). We define the pulse spreading time as a "OPPM slot," and one OPPM slot corresponds to the

length of code sequence. We assume  $L = 20$ ,  $\omega = 4$ , and the weighted positions of the desired user are (0, 3, 11, 15). The OPPM-CDMA scheme allows the OPPM slots to overlap each other [9]. Therefore, the OPPM-CDMA system can increase the code length and number of weights compared to the PPM-CDMA system under the condition that the bandwidth and number of subscribers are constant, and can maintain the advantages of power-efficiency and pulse position multiplicity in the PPM. As a result, the OPPM-CDMA system achieves higher tolerance to MAI, which results in improvement of BEP compared to the PPM-CDMA systems [9]. Fig. 4 shows an example of transmissions of the four service classes in the proposed multi-rate and multi-BEP scheme which are (a)  $M = 4$  and high-power, (b)  $M = 4$  and low-power, (c)  $M = 8$  and high-power, and (d)  $M = 8$  and low-power. Here the class A, B, and C meet the applications such as real-time video streaming transmissions, real-time voice transmissions, image data transmission, respectively. The class D does not guarantee both bit rate and BEP (i.e., the class with lowest priority, that is, best-effort type). The code length and number of weights can be kept constant among all service classes at the same bandwidth (chip-duration). This means that one user requires only one code sequence for the four service classes. Note that the proposed system requires the code reconfiguration at the same code length and number of weights only when a user changes the destination. In addition, it is very difficult to frequently change the chip-rate for the differentiation of service classes in the optical CDMA systems because the time-width of a pulse needs to be changed depending on the service class, which causes the increase of complexity in the laser-diode. Therefore, the proposed scheme which does not need to change the chip-rate achieves simple system configuration. The systems with  $M = 4$  and  $M = 8$  transmit two and three bits at the four and the eight slots, respectively. This means that the bit-rate of the service class with  $M = 4$  is four-thirds of the one with  $M = 8$ , and  $M = 4$  and  $M = 8$  correspond to the high-rate and the low-rate, respectively. The service class with the high-power achieves the lower BEP than that with the low-power. Therefore, the cases of (a), (b), (c), and (d) in Fig. 4 correspond to class A, class B, class C, and class D as we define in Section I, respectively.

### III. THEORETICAL ANALYSIS

In this paper, we assume that the received optical power is large enough to eliminate the effect of noises in the photo-diode in order to clarify the fundamental performance of the proposed scheme due to the effect of MAI. In addition, we consider a network system in which the total transmission distance is short such as star formed LANs or access networks [1], [2], where we can assume that there are no effects due to attenuation, nonlinear characteristic, and dispersions through a fiber in this analysis. In addition, we assume that a frame is asynchronous among users, and the transmissions among users are chip-synchronous because the performance in the chip-synchronous case results in the upper bound on the performance of the asynchronous system [8]. Also, we assume that the output of OHL is ideal in this paper.

First, in order to easily understand the theoretical analysis of

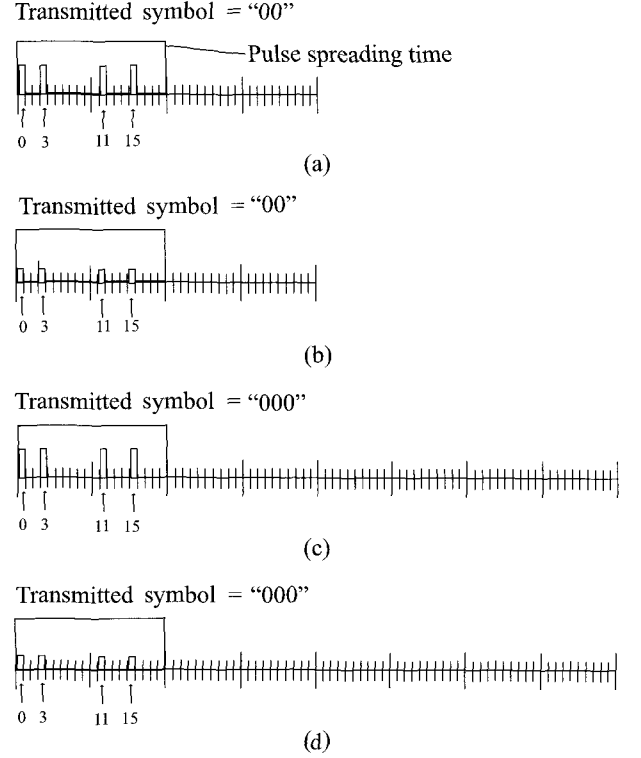


Fig. 4. An example of the transmissions of the four service classes ( $\gamma = 2$ ): (a) High-rate ( $M = 4$ ), low-BEP (high power), (b) high-rate ( $M = 4$ ), high-BEP (low power), (c) low-rate ( $M = 8$ ), low-BEP (high power), (d) low-rate ( $M = 8$ ), high-BEP (low power).

the proposed system, we describe an upper bound on the BEP of the conventional single-rate OPPM-CDMA system. We assume that the desired user transmits optical pulses at the 0-th OPPM slot. We denote the correlator output in the  $j$ -th OPPM slot by  $Y_j$ . We also denote the number of simultaneous users and the number of MAI in the  $j$ -th OPPM slot by  $N$  and  $\kappa_j$ , respectively. The reference [9] shows that an upper bound on the symbol error probability of the single-rate OPPM-CDMA system,  $P_{S, \text{OPPM}}$ , is expressed as

$$P_{S, \text{OPPM}} \leq \sum_{l=0}^{N-1} \left( (M-1) \Pr(Y_1 \geq Y_0 | \kappa_0 = 0, \kappa_1 = l, \nu_1 = 0) + (\gamma - 1) \frac{\omega(\omega - 1)}{L - 1} \{ \Pr(Y_1 \geq Y_0 | \kappa_0 = 0, \kappa_1 = l, \nu_1 = 1) - \Pr(Y_1 \geq Y_0 | \kappa_0 = 0, \kappa_1 = l, \nu_1 = 0) \} \right) \Pr(\kappa_1 = l). \quad (1)$$

Here,  $\nu_1$  is the number of self-interference where an transmitted optical pulse in the 0-th OPPM slot interferes with a weighted position in the 1st OPPM slot. In the absence of APD noise and thermal noise,  $Y_1 \geq Y_0$  corresponds to the relation  $l = \omega$  in the case of  $\nu_1 = 0$ , or  $l = \omega - 1$  in the case of  $\nu_1 = 1$ .  $\Pr(\kappa_1 = l)$  is expressed as [9]

$$\Pr(\kappa_1 = l) = \binom{N-1}{l} \left( \frac{\gamma\omega^2}{ML} \right)^l \left( 1 - \frac{\gamma\omega^2}{ML} \right)^{N-1-l}. \quad (2)$$

The BEP of the single-rate system,  $P_{b, \text{OPPM}}$ , can be obtained

from the relation  $P_{b, \text{OPPM}} = \{M/2(M-1)\}P_{s, \text{OPPM}}$ .

Next, we analyze the BEPs of the proposed multi-rate and multi-BEP system. The BEPs of the four service classes can be obtained based on the BEP of the single-rate OPPM-CDMA system (i.e., (1)). We denote the numbers of simultaneous other users (i.e., except the desired user) with class A, B, C, and D by  $n_A, n_B, n_C$ , and  $n_D$ , respectively.

First, we analyze the BEP for the user with class B (high-rate and high-BEP) and class D (low-rate and high-BEP). As in the single-rate OPPM-CDMA system, we derive an upper bound on the BEP by focusing attention on only the number of MAI at the 1st OPPM slot and by assuming that the MAI interfering with the weighted positions at the "0"-th slot does not exist. We denote the correlator output in the  $j$ -th OPPM slot by  $Y_j$ , and the number of self-interference where an transmitted optical pulse in the 0th OPPM slot interferes with a weighted position in the 1st OPPM slot by  $\nu_1$ . We also denote the numbers of MAI from the other users with class A, class B, class C, and class D in 1st OPPM slot by  $u_A, u_B, u_C$  and  $u_D$ , respectively, and total summation is  $I = u_A + u_B + u_C + u_D$  ( $0 \leq u_A \leq n_A, 0 \leq u_B \leq n_B, 0 \leq u_C \leq n_C$  and  $0 \leq u_D \leq n_D$ ). In addition, we denote the numbers of MAI with the low-intensity and the high-intensity on the  $\beta$ -th weighted position at the 1st OPPM slot by  $l_{\beta l}$  and  $l_{\beta h}$  ( $\beta \in 1, 2, \dots, \omega; 0 \leq l_{\beta h} \leq (u_A + u_C), 0 \leq l_{\beta l} \leq (u_B + u_D)$ ), respectively, where  $\omega$  is the number of weights. We define the interference state pattern vectors in each weighted position as follows.

$$\mathbf{l}_h = (l_{1h}, l_{2h}, \dots, l_{\omega h}) \quad (3)$$

$$\mathbf{l}_l = (l_{1l}, l_{2l}, \dots, l_{\omega l}). \quad (4)$$

This means that  $u_A + u_C = l_{1h} + l_{2h} + \dots + l_{\omega h}$  and  $u_B + u_D = l_{1l} + l_{2l} + \dots + l_{\omega l}$ . Here, we define the interference state pattern vector  $\mathbf{l} = \mathbf{l}_h + \mathbf{l}_l = (l_1, l_2, \dots, l_\omega)$  and the number of nonzero elements in  $\mathbf{l}$  by  $|\mathbf{l}|$ . We denote the occurrence probabilities of the interfering users with class A, class B, class C, and class D by  $\Pr(u_A|n_A), \Pr(u_B|n_B), \Pr(u_C|n_C)$ , and  $\Pr(u_D|n_D)$ , respectively. The probabilities are expressed as

$$\begin{aligned} \Pr(u_\epsilon|n_\epsilon) &= \binom{n_\epsilon}{u_\epsilon} \left(\frac{\gamma\omega^2}{M_h L}\right)^{u_\epsilon} \left(1 - \frac{\gamma\omega^2}{M_h L}\right)^{n_\epsilon - u_\epsilon} \\ \Pr(u_\zeta|n_\zeta) &= \binom{n_\zeta}{u_\zeta} \left(\frac{\gamma\omega^2}{M_l L}\right)^{u_\zeta} \left(1 - \frac{\gamma\omega^2}{M_l L}\right)^{n_\zeta - u_\zeta} \end{aligned} \quad (5)$$

where  $\epsilon \in A, B$  and  $\zeta \in C, D$ , and  $M_h$  and  $M_l$  are the value of  $M$  corresponding to the high-rate and the low-rate, respectively. Then, the symbol error probability for the user with class B in the proposed system,  $P_{s,B}$ , is based on (1) (i.e., the symbol error probability of the single-rate OPPM system), and is obtained as

$$\begin{aligned} P_{s,B} &\leq \sum_{u_A=0}^{n_A} \sum_{u_B=0}^{n_B} \sum_{u_C=0}^{n_C} \sum_{u_D=0}^{n_D} \\ &\left( (M_h - 1) \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0) \right. \\ &\quad \left. + (\gamma - 1) \frac{\omega(\omega - 1)}{L - 1} \left\{ \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 1) \right. \right. \\ &\quad \left. \left. - \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0) \right\} \right) \\ &\quad \times \Pr(u_A|n_A) \Pr(u_B|n_B) \Pr(u_C|n_C) \Pr(u_D|n_D). \end{aligned} \quad (6)$$

In the absence of APD noise and thermal noise,  $Y_1 \geq Y_0$  corresponds to the relation  $|\mathbf{l}| = \omega$  in the case of  $\nu_1 = 0$ , or  $|\mathbf{l}| = \omega - 1$  in the case of  $\nu_1 = 1$ . Therefore,  $\Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0)$  and  $\Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 1)$  are expressed as  $\Pr(|\mathbf{l}| = \omega | u_A, u_B, u_C, u_D)$  and  $\Pr(|\mathbf{l}| = \omega - 1 | u_A, u_B, u_C, u_D)$ , respectively.  $\Pr(|\mathbf{l}| = \omega | u_A, u_B, u_C, u_D)$  is expressed as

$$\Pr(|\mathbf{l}| = \omega | u_A, u_B, u_C, u_D) = \sum_{\mathbf{l} \in G_I, |\mathbf{l}| = \omega} NDP(\mathbf{l}) P(\mathbf{l}; H_I) \quad (7)$$

where  $H_I$  is the set of all interference pattern vectors with total weights equal to  $I$ .  $G_I$  is the set of representative interference vectors in  $H_I$  with elements in decreasing order. Here,  $\Pr(|\mathbf{l}| = \omega - 1 | u_A, u_B, u_C, u_D)$  is obtained by changing from " $\omega$ " to " $\omega - 1$ " in (7).  $NDP(\mathbf{l})$  is the number of distinct permutations of the vector  $\mathbf{l}$  in  $G_I$  and expressed as [8]

$$NDP(\mathbf{l}) = \frac{\omega!}{\prod_{i=1}^{\omega} R(l_i)!} \quad (8)$$

where  $R(l_i)$  ( $1 \leq i \leq \omega$ ) is the number of repetition times of an element  $l_i$  in the vector  $\mathbf{l}$  and the product is taken over  $i$  for which  $l_i$  is distinct.  $P(\mathbf{l}; H_I)$  is the multinomial distribution for the interference pattern vector  $\mathbf{l}$  in  $H_I$  and expressed as [8]

$$P(\mathbf{l}; H_I) = \frac{I!}{\omega^I \prod_{i=1}^{\omega} (l_i!)} \quad (9)$$

The BEP of class B in the proposed system  $P_{b,B}$  can be obtained from the following relation.

$$P_{b,B} = \{M_h/2(M_h - 1)\}P_{s,B}. \quad (10)$$

The BEP of class D,  $P_{b,D}$ , can be obtained by changing from  $M_h$  in (5) and (10) to  $M_l$ , and the desired user transmits the pulses with class D instead of class B. Therefore, the two BEPs of class B and class D are slightly different. However, since the two classes have the similar effects of MAI each other, we can expect that their BEPs are similar.

Next, we analyse the BEP for the user with class A and class C (i.e., low-BEP class),  $P_{b,A}$  and  $P_{b,C}$ . Here, we define the optical intensity of the high-power pulse and that of the low-power as  $P_h$  and  $P_l$ , respectively, and the optical power ratio  $R = P_h/P_l$ . We also define the interference state pattern vector  $\mathbf{l}'_i = (l'_{1i}, l'_{2i}, \dots, l'_{\omega i})$  as follows.

- If  $l_{\beta l}$  in  $\mathbf{l}_l$  exceeds  $P_h/P_l$ , the value is "1," ( $1 \leq \beta \leq \omega$ ).
- Otherwise, the value is "0."

In addition, we define the logical addition of two interference state pattern vector  $\mathbf{l}'_i \cup \mathbf{l}_h$  as  $\mathbf{J}$ , and the number of nonzero elements in  $\mathbf{J} = (J_1, J_2, \dots, J_\omega)$  by  $|\mathbf{J}|$ . The occurrence probabilities of the interfering users with class A, class B, class C, and class D (i.e.,  $\Pr(u_A|n_A), \Pr(u_B|n_B), \Pr(u_C|n_C)$ , and  $\Pr(u_D|n_D)$ ) are the same as the cases of class B and class D,

and is expressed as (5). Then, the symbol error probability of class A,  $P_{s,A}$ , is based on (1) (i.e., the symbol error probability of the single-rate OPPM system) just as the cases of class B and class D, and is expressed as

$$P_{s,A} \leq \sum_{u_A=0}^{n_A} \sum_{u_B=0}^{n_B} \sum_{u_C=0}^{n_C} \sum_{u_D=0}^{n_D} \left( (M_h - 1) \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0) + (\gamma - 1) \frac{\omega(\omega - 1)}{L - 1} \{ \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 1) - \Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0) \} \right) \times \Pr(u_A | n_A) \Pr(u_B | n_B) \Pr(u_C | n_C) \Pr(u_D | n_D). \quad (11)$$

In the absence of APD noise and thermal noise,  $Y_1 \geq Y_0$  corresponds to the relation  $|\mathbf{J}| = \omega$  in the case of  $\nu_1 = 0$ , or  $|\mathbf{J}| = \omega - 1$  in the case of  $\nu_1 = 1$ . Therefore,  $\Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 0)$  and  $\Pr(Y_1 \geq Y_0 | u_A, u_B, u_C, u_D; \nu_1 = 1)$  are expressed as  $\Pr(|\mathbf{J}| = \omega | u_A, u_B, u_C, u_D)$  and  $\Pr(|\mathbf{J}| = \omega - 1 | u_A, u_B, u_C, u_D)$ , respectively.  $\Pr(|\mathbf{J}| = \omega | u_A, u_B, u_C, u_D)$  is expressed as

$$\Pr(|\mathbf{J}| = \omega | u_A, u_B, u_C, u_D) = \sum_{l_{1l}=0}^{I_l} \sum_{l_{2l}=0}^{I_l - l_{1l}} \cdots \sum_{l_{(\omega-1)l}=0}^{I_l - l_{1l} - \cdots - l_{(\omega-2)l}} \sum_{\mathbf{l}_h \in G_{I_h}, |\mathbf{J}|=\omega} NDP(\mathbf{l}_h) P(\mathbf{l}_h; H_{I_h} | I_h = u_A + u_C) \times P(\mathbf{l}_l; H_{I_l} | I_l = u_B + u_D = l_{1l} + l_{2l} + \cdots + l_{\omega l}) \quad (12)$$

where  $H_{I_h}$  and  $H_{I_l}$  are the set of all interference pattern vectors with total weights equal to  $I_h$  and  $I_l$ , respectively.  $G_{I_h}$  is the set of representative interference vectors in  $H_{I_h}$  with elements in decreasing order. Here,  $\Pr(|\mathbf{J}| = \omega - 1 | u_A, u_B, u_C, u_D)$  is obtained by changing from “ $\omega$ ” to “ $\omega - 1$ ” in (12).  $NDP(\mathbf{l}_h)$  is the number of distinct permutations of the vector  $\mathbf{l}_h$  in  $G_{I_h}$  and expressed as

$$NDP(\mathbf{l}_h) = \frac{\omega!}{\prod_{i_h=1}^{\omega} R(l_{i_h})!} \quad (13)$$

where  $R(l_{i_h})$  ( $1 \leq i_h \leq \omega$ ) is the number of repetition times of an element  $l_{i_h}$  in the vector  $\mathbf{l}_h$  and the product is taken over  $i_h$  for which  $l_{i_h}$  is distinct.  $P(\mathbf{l}_l; H_{I_l})$  and  $P(\mathbf{l}_h; H_{I_h})$  are the multinomial distributions for the interference pattern vectors  $\mathbf{l}_l$  in  $H_{I_l}$  and  $\mathbf{l}_h$  in  $H_{I_h}$ , respectively, and expressed as

$$P(\mathbf{l}_\xi; H_{I_\xi}) = \frac{I_\xi!}{\omega^{I_\xi} \prod_{i_\xi=1}^{\omega} (l_{i_\xi}!)} \quad (14)$$

where  $\xi \in l, h$ . The BEP of class A in the proposed system,  $P_{b,A}$ , can be obtained from the following relation

$$P_{b,A} = \{M_h/2(M_h - 1)\} P_{s,A}. \quad (15)$$

The BEP of class C,  $P_{b,C}$ , can be obtained by changing from  $M_h$  in (11) and (15) to  $M_l$ , and the desired user transmits the

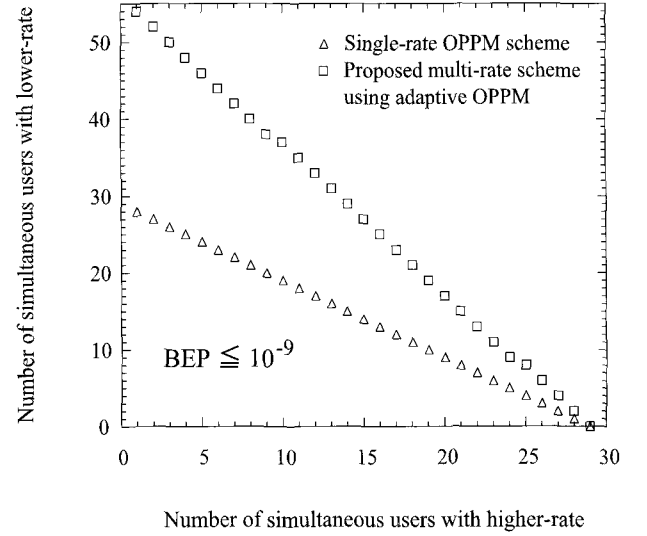


Fig. 5. Number of simultaneous users with higher-rate versus the number of simultaneous users with lower-rate at  $\text{BEP} \leq 10^{-9}$ ,  $L = 4500$ ,  $\omega = 5$ ,  $\gamma = 9$ .

pulses with class C instead of class A. Therefore, the two BEPs of class A and class C are slightly different. However, since the two classes have similar effects of MAI, we can expect that their BEPs are similar.

#### IV. NUMERICAL RESULT

In this paper, the code length  $L$ , the number of weights  $\omega$ , and the chip duration  $T_c$  are kept constant among all service classes. We define the numbers of simultaneous users with class A, class B, class C, and class D as  $N_A$ ,  $N_B$ ,  $N_C$ , and  $N_D$ , respectively. This means that, if the desired user transmits the pulse with class A, we can obtain the relations as  $N_A = n_A + 1$ ,  $N_B = n_B$ ,  $N_C = n_C$ , and  $N_D = n_D$ . Then, the total number of simultaneous users  $N = N_A + N_B + N_C + N_D$ .

First, we clarify the effectiveness of the proposed adaptive OPPM (multi-rate) scheme compared to the single-rate OPPM scheme. Fig. 5 shows the number of simultaneous users with the high-rate versus the number of simultaneous users with the low-rate under the condition that  $\text{BEP} \leq 10^{-9}$ . We set  $L = 4500$ ,  $\omega = 5$ ,  $\gamma = 9$ , and we assume that all users transmit pulses with the same optical power (i.e., the system without the power controller) to clarify the effectiveness of the proposed adaptive OPPM scheme. The values of  $M$  for the high-rate and the low-rate, that are  $M_h$  and  $M_l$ , are 32 and 64, respectively. This means that the high-rate and the low-rate correspond to 100 Mbps and 60 Mbps, respectively. We also assume that the desired user is one of the high-rate users. We can see that the proposed multi-rate scheme can accommodate more simultaneous users than the single-rate OPPM scheme. This reason is as follows. In the single-rate OPPM scheme, since the system can accommodate only fixed single-rate, the high-rate is assigned to all users even if some users require the lower-rate. This means that the single-rate scheme causes the waste of bandwidth. On the other hand, in the proposed adaptive OPPM scheme, the corresponding required minimum bit rate is assigned to each user,

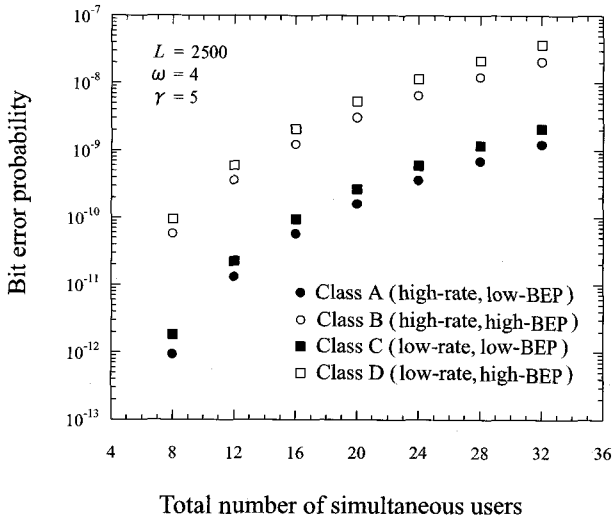


Fig. 6. Total number of simultaneous users  $N$  versus bit error probability of the four classes where  $N_A = N_B = N_C = N_D = N/4$  and  $L = 2500$ ,  $\omega = 4$ ,  $\gamma = 5$ ,  $R = 5$ .

which results in effective utilization of the bandwidth. Therefore, the proposed multi-rate scheme can increase the number of simultaneous users as long as it achieves the  $\text{BEP} \leq 10^{-9}$ . Note that, when all users belong to the high-rate users, the proposed multi-rate scheme is the same as the single-rate scheme.

Next, we clarify the performance of the proposed multimedia (i.e., “multi-rate” and “multi-BEP”) scheme. Since the main advantage of the proposed multi-rate scheme compared to the conventional multi-rate scheme (i.e., the scheme by changing the code sequence) is its simplicity of the system configuration, we do not dare to compare the performances of both schemes in this paper. We would rather show that the proposed multimedia scheme can achieve distinct differentiation of the four service classes (i.e., class A, B, C, and D). Fig. 6 shows the total number of simultaneous users  $N$  versus BEP where the service classes are class A (high-rate, low-BEP), class B (high-rate, high-BEP), class C (low-rate, low-BEP), and class D (low-rate, high-BEP). The four classes correspond to “ $M_h = 32$  and high-power,” “ $M_h = 32$  and low-power,” “ $M_l = 64$  and high-power,” and “ $M_l = 64$  and low-power,” respectively, in the proposed multi-rate and multi-BEP system. We set  $L = 2500$ ,  $\omega = 4$ , and  $\gamma = 5$ , and assume that the bit rates of  $M_h = 32$  and  $M_l = 64$  are 100 Mbps and 60 Mbps, respectively. We also set the optical power ratio  $R = 5$ . In Fig. 6, we assume the uniform distribution where the numbers of simultaneous users are the same among all service classes (i.e.,  $N_A = N_B = N_C = N_D = N/4$ ). We can see that the BEPs of the four service classes are well divided into four cases which are the class A, B, C, and D. The control for the value of  $M$  achieves the various bit rates without changing the code sequence. On the other hand, the control for the transmitted power achieves the various BEPs, and the users with the high-power can achieve lower BEP than the ones with the low-power because the OHL with the high-power is easier to eliminate the MAI with the low-power while the OHL with the low-power cannot eliminate them. The proposed system with power controller strives to improve the BEP of the users who require lower-BEP as much as possible by assigning

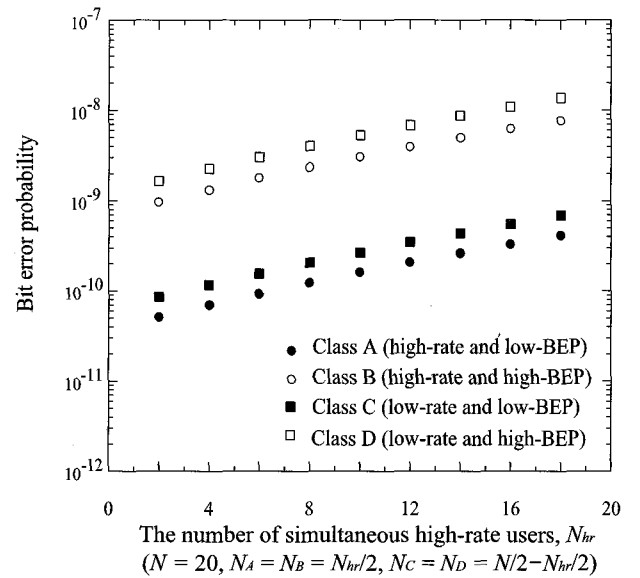


Fig. 7. Total number of simultaneous high-rate ( $M_h = 32$ ) users  $N_{hr}$  versus bit error probability of the four classes where  $N = 20$ ,  $L = 2500$ ,  $\omega = 4$ ,  $\gamma = 5$ ,  $R = 5$ .

the lower-power to the users who accept higher-BEP (i.e., low-priority). Generally, in the single-rate optical OPPM-CDMA system, the system with  $M = 64$  achieves better performance than that with  $M_h = 32$  because of the pulse position multiplicity. However, in the proposed multi-rate transmission, the effect of MAI originating from the other users with  $M_l = 64$  decreases for the user with  $M_h = 32$  because the number of MAI per unit time decreases, while the effect of MAI originating from the other users with  $M_h = 32$  becomes larger for the user with  $M_l = 64$ . Therefore, the performances of  $M_h = 32$  and  $M_l = 64$  become similar each other. The optical OPPM-CDMA systems compare the output of the OPPM slot in which the desired user transmits the pulse with the outputs of the other OPPM slots [9]. This means that the MAI in the weighted positions at the OPPM slot in which the desired user transmits the pulse does not matter in terms of the BEP. Since the system with  $M_l = 64$  has more number of the other OPPM slots in which the desired user does not transmit the optical pulse, the BEP of  $M_l = 64$  is slightly worse than that of  $M_h = 32$ .

Fig. 7 shows the number of simultaneous “high-rate” ( $M_h = 32$ ) users,  $N_{hr}$ , versus BEP where  $L = 2500$ ,  $\omega = 4$ ,  $\gamma = 5$  and  $R = 5$ . In Fig. 7, we assume that the number of users with low-BEP is the same as the one with high-BEP, and set  $N = 20$ ,  $N_A = N_B = N_{hr}/2$ , and  $N_C = N_D = N/2 - N_{hr}/2$ . We can see that the BEPs of all service classes degrade as the value of  $N_{hr}$  becomes large. This is because, as the number of users with  $M_h = 32$  increases, the transmitted pulses from the users per time increase and the effects of MAI become larger for all users.

Fig. 8 shows the number of simultaneous “low-BEP” (high-power) users,  $N_{lB}$ , versus BEP where  $L = 2500$ ,  $\omega = 4$ ,  $\gamma = 5$ , and  $R = 5$ . In Fig. 8, we assume that the number of users with the high-rate is the same as that with the low-rate, and set  $N = 20$ ,  $N_A = N_C = N_{lB}/2$ , and  $N_B = N_D = N/2 - N_{lB}/2$ . We can see that the BEPs of the users with high-BEP are con-

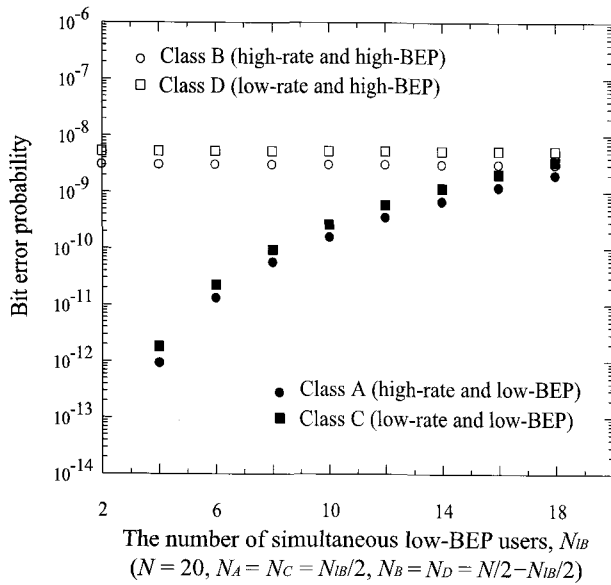


Fig. 8. The number of simultaneous low-BEP (high-power) users  $N_{IB}$  versus bit error probability of the four classes where  $N = 20$ ,  $L = 2500$ ,  $\omega = 4$ ,  $\gamma = 5$ ,  $R = 5$ .

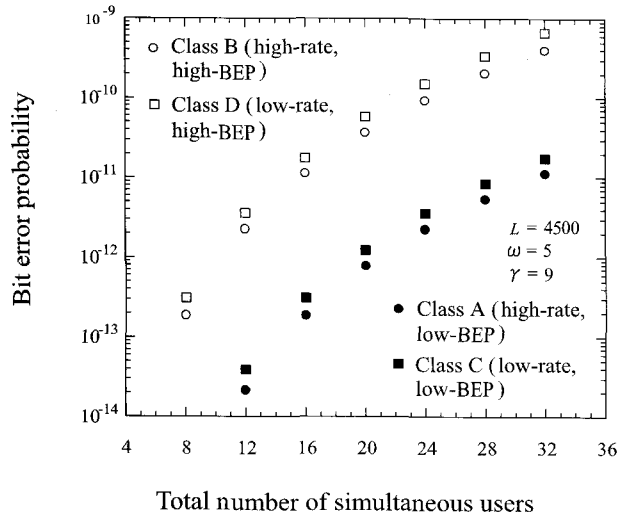


Fig. 9. Total number of simultaneous users  $N$  versus bit error probability of the four classes where  $N_A = N_B = N_C = N_D = N/4$ , and  $L = 4500$ ,  $\omega = 5$ ,  $\gamma = 9$ ,  $R = 5$ .

stant in any values of  $N_{IB}$ . This reason is as follows; The OHL with the low-level threshold clips at the low intensity independent of the intensity of the incoming pulse, and the effect of MAI on the users with high-BEP (low-power) does not depend on the intensity of MAI. This means that the effect of MAI on the users with high-BEP does not depend on the value of  $N_{IB}$ , but depends on only value of  $N$ . We can also see that the gap between the BEPs of the users with high-BEP and those with low-BEP decreases as the value of  $N_{IB}$  becomes large. This is because, as the users with the high-power increases, the effect of MAI for the users with the high-power becomes larger. In the case of Fig. 8, the distinct differentiation of the service classes can be achieved in the range of  $N \leq 14$ .

Fig. 9 shows the total number of simultaneous users  $N$  versus

BEP where  $\gamma = 9$  compared to the case of Fig. 6 ( $\gamma = 5$ ). This corresponds to  $L = 4500$  and  $\omega = 5$  at the same bandwidth and number of subscribers [6]. We also set  $R = 5$ . As we show in Fig. 9, the BEPs of the four service classes are well divided into four cases which are the class A, B, C, and D. Also, we can see that the BEPs of all service classes are lower than those in Fig. 6. This is because, as the value of  $\gamma$  increases, the values of  $L$  and  $\omega$  increases, which results in the smaller effect of MAI.

## V. CONCLUSION

We have proposed the multimedia (i.e., multi-rate and multi-BEP) transmission scheme using adaptive OPPM and power controller in optical CDMA systems. The proposed adaptive OPPM for the multi-rate transmission has the advantage that it does not need to change the code sequence depending on the required bit rate of the user and can easily change the bit-rate in the electronic domain. This results in the simpler system configuration than the conventional multi-rate schemes which need to change the code sequence in the optical domain. Moreover, the proposed adaptive OPPM has the other advantage that the difference of the bit rates does not have so much effect on the BEP. In addition, the optical power controller for multi-BEP requires only power attenuator, and the difference of the transmitted power does not cause the change of the bit rate. Thus, the proposed scheme using the adaptive OPPM and power controller can easily achieve the distinct differentiation of many multimedia services by using the combination of  $M$  and optical transmitted power. We analyze the BEPs of the four service classes which correspond to “high-rate ( $M = 32$ ), low-BEP (high-power),” “high-rate ( $M = 32$ ), high-BEP (low-power),” “low-rate ( $M = 64$ ), low-BEP (high-power),” and “low-rate ( $M = 64$ ), high-BEP (low-power).” We show that the multi-rate transmission system using the proposed adaptive OPPM can accommodate more simultaneous users than the single-rate OPPM system at the  $\text{BEP} \leq 10^{-9}$ . We also show that the proposed multi-rate and multi-BEP system can achieve distinct differentiation of the four service classes without changing the code sequence depending on the service class of the user.

In this study, we have considered only four kinds of service classes, and the QoS characteristics of the service classes are not so much different. However, we can expect that data traffic with more service classes will appear in future optical networks. In addition, it would be much more interesting if the service classes were very different in bit-rate and BEP. Therefore, we will consider how to achieve a distinct differentiation of more service classes in future works.

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