

An OCDMA Scheme to Reduce Multiple Access Interference and Enhance Performance for Optical Subscriber Access Networks

Sangjo Park, Bong Kyu Kim, and Byoung Whi Kim

We propose a new optical code division multiple access (OCDMA) scheme for reducing multiple access interference (MAI) and enhancing performance for optical subscriber access networks using modified pseudorandom noise (PN)-coded fiber Bragg gratings with bipolar OCDMA decoders. Through the bipolar OCDMA decoder and the modified PN codes, MAI among users is effectively depressed. As the data are encoded either by a unipolar signature sequence of the modified PN code or its complement according to whether the data bit is 1 or 0, the bit error ratio (BER) can be more improved with the same signal to interference plus noise ratio over the conventional on-off shift keying-based OCDMA system. We prove by numerical analysis that the BER of the proposed bipolar OCDMA system is better than the conventional unipolar OCDMA system. We also analyze the spectral power distortion effects of the broadband light source.

Keywords: Optical CDMA, modified PN codes, bipolar, fiber Bragg grating (FBG), multiple access interference (MAI).

I. Introduction

A future subscriber access system needs a broadband transmission link that offers interactive multimedia services, such as voice, high quality video-on-demand, and high speed data. Fiber-optic transmission systems, such as the fiber-to-the-home and the fiber-to-the-curb, have been introduced into subscriber access networks to provide high transmission quality. Figure 1 shows an ATM-based passive optical network (PON) in which several optical network units (ONUs) are connected to an ATM-based optical line termination (OLT) by an optical fiber [1]. In this ATM-based PON system, the ATM cells supply residential customers with services such as high quality TV, Internet protocol and digital video-on-demand. Moreover, non-ATM services, such as public switched telephone networks (PSTNs), narrowband integrated service digital networks (NISDNs), and power digital subscriber lines (DSLs) can be provided [2].

ATM-based PON technology using optical splitters is preferable for optical subscriber access networks because it provides low cost and flexible sharing of the resource bandwidth. Therefore, we consider the PON structure as an effective multiple access method for the optical subscriber access network. We investigated the multiple access method for the up-link of the ATM-based PON because conventional multiplexing methods, such as time division multiple access (TDMA), are applied to the down-link and for the sake of a simple analysis. TDMA is one of the solutions that are suitable for the up-link of the ATM-based PON for sharing the bandwidth of optical channels. However, the TDMA-based

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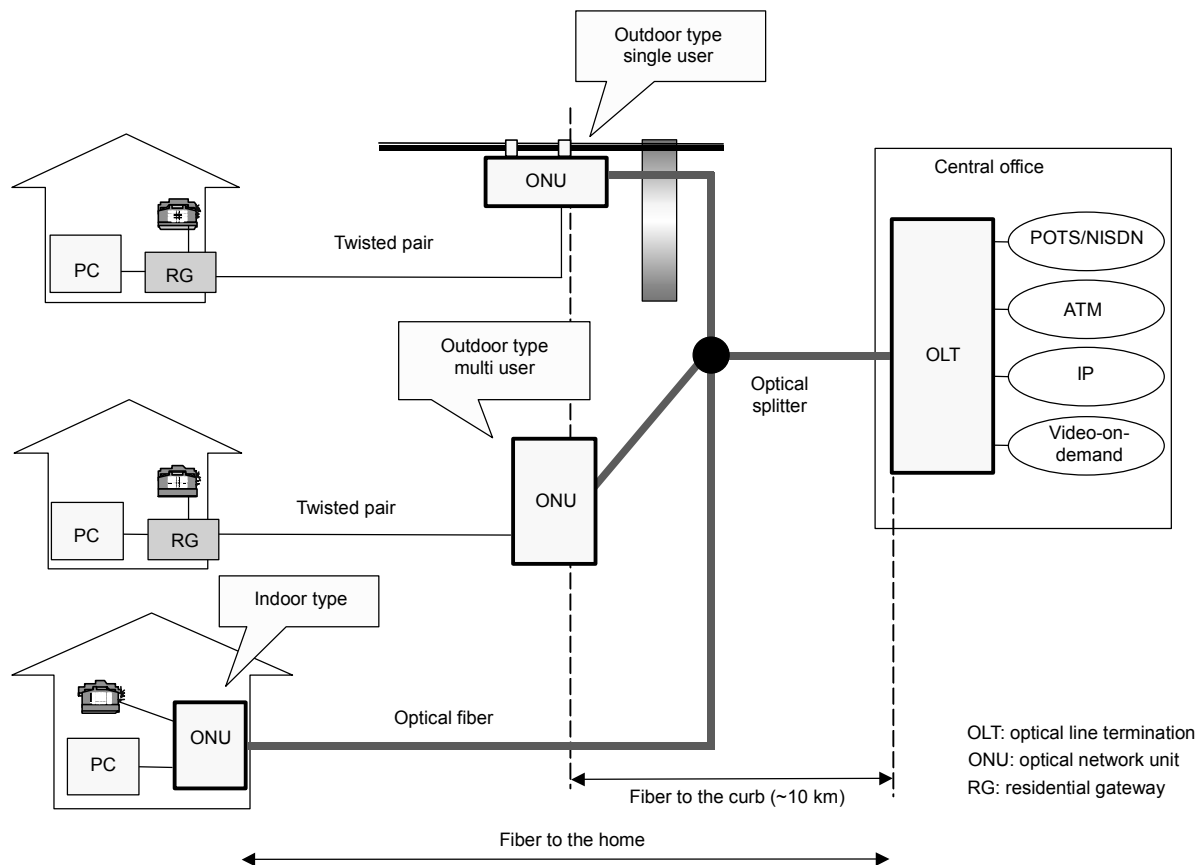


Fig. 1. ATM-based PON system.

PON has to solve many problems, such as medium access control (MAC) for precise packet interleaving, access delay, and clock phase alignment. Thus, code division multiple access (CDMA) is a strong candidate for creating effective multiple methods [3] for the optical subscriber access network because of its asynchronous access and code multiplexing [4], [5].

Moreover, the optical CDMA method is preferable for multiplexing in the optical domain because it uses broad bandwidths in optical devices for the electrical CDMA method [6] and the E/O conversion. Thus, we propose a fiber-optic asynchronous subscriber access system for optical subscriber access networks with a new optical CDMA (OCDMA) method.

Up to this time, OCDMA methods have been studied and developed for optical systems, such as local area networks (LANs), because of their asynchronous access properties. The main OCDMA methods use the following: optical delay lines [7], [8] or optical switches [9]–[11] with optical orthogonal code (OOC) for the time domain; fiber Bragg grating (FBG) or arrayed waveguide gratings (AWGs) and OOCs for the optical frequency domain [12]; and FBGs or AWGs for optical

wavelength-hopping/time spreading [13], [14]. OCDMA using OOCs has many problems, such as a limitation on the number of distinct code sequences and low optical power because there are fewer 1s than 0s.

One of the key issues for OCDMA is to reduce the multiple access interference (MAI) among channels (or users). One study proposed an FBG-based OCDMA with maximal length codes to reduce MAI, where only data 1 is encoded as in the conventional OCDMA on-off shift keying; it has a unipolar capacity [15]. Furthermore, the spectral power distortion effects of the broadband light source were not considered.

In this paper, we propose a new method for optical subscriber access to reduce multiple access interference and enhance performance in optical frequency domain OCDMA systems. Because all data are encoded during half of the modified PN sequences, the bit error rates (BERs) with a bipolar OCDMA decoder [16] are better than when there is a unipolar decoder. We also propose modified PN codes to reduce the MAI with a bipolar OCDMA decoder. Through the bipolar OCDMA decoder and modified PN codes, digital data can be regenerated without MAI among users. We also discuss

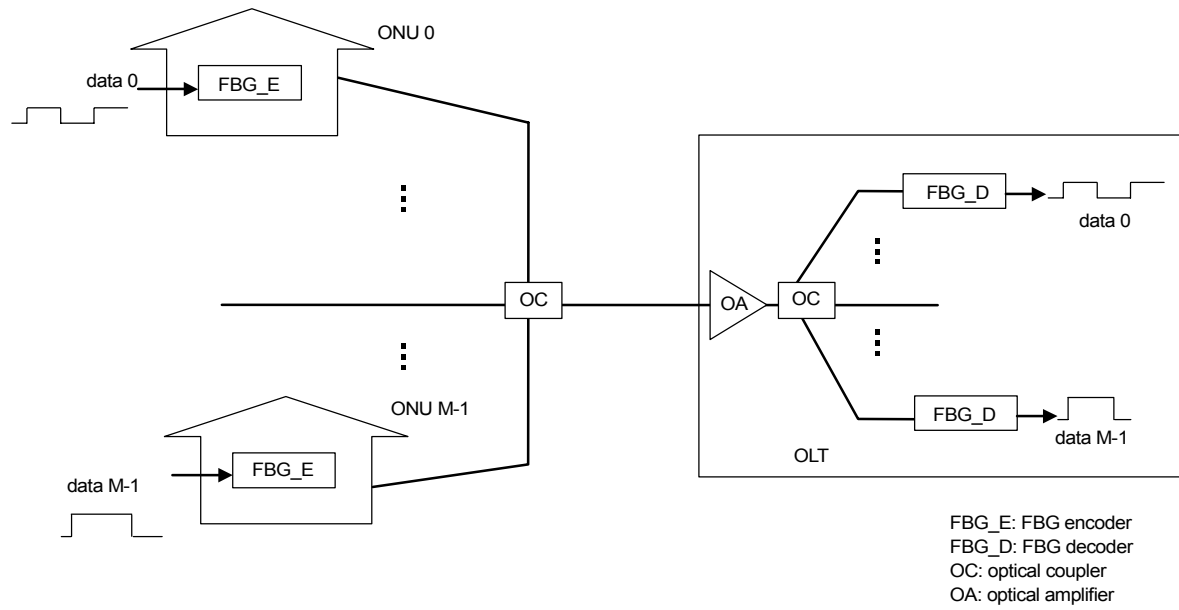


Fig. 2. Optical subscriber access system using OCDMA with modified PN codes and FBGs.

the effect of the spectral power distortion of the broadband light source and the noise components.

II. Optical Subscriber Access System Using OCDMA with Modified PN Codes and FBGs

The optical subscriber access system using OCDMA with modified PN codes and FBGs is shown in Fig. 2. M ONUs are connected to a fiber-optic link by using an $n:1$ optical coupler, where data are multiplexed by the CDMA scheme at the FBG encoder. M optical coded signals are transmitted to an OLT. At the OLT, an optical amplifier is equipped to compensate for the optical loss of one optical coupler and M optical coded signals from M ONUs are power split into each of n FBG decoders and then correlated with one of the same code patterns at the FBG encoder.

In the conventional OCDMA with a bipolar capacity using PN codes, such as gold codes and maximal length codes, MAI takes place because the number of 0s is not equal to the number of 1s. The modified PN codes have the same number of 1s and 0s to eliminate the MAI. Table 1 illustrates the modified PN code sequences for a code length (n) of 8 as an example. User $\#j$ is assigned by modified PN code sequences, $C_j = (C_j(0), C_j(1), \dots, C_j(n-1))$. The stuff bit of 0 is inserted at the end of each code in order to equalize the numbers of 1s and 0s. Thus, modified PN code sequences have an even code length and equal number of 1s and 0s.

Figure 3 depicts the FBG encoder and decoder for an optical subscriber access system. We used a broadband optical source

ONU no.	Code sequence							
0	1	1	1	0	0	1	0	0
1	0	1	1	1	0	0	1	0
2	1	0	1	1	1	0	0	0
3	0	1	0	1	1	1	0	0
4	0	0	1	0	1	1	1	0
5	1	0	0	1	0	1	1	0
6	1	1	0	0	1	0	1	0
PN code								Stuff bit

Table 1. Modified PN code sequences for the code length of 8.

such as a super luminescence diode and inserted a bandpass filter at its output port to split the light source with a spectrally uniform shape. Uniformly split light source streams are directed to the FBG encoder for the spectral encoding. The transmitted light field and the reflected light field from the FBGs are inversely encoded in the wavelength domain due to the transmission and the reflection characteristics of the FBG as $\overline{C_j}$ and C_j , respectively, at the ONU $\#j$. A 2×1 optical switch, such as a Mach-Zehnder intensity modulator, selects the reflected light field if the data bit is 1 or the transmitted light field if the data bit is 0. At the FBG encoder, the data are encoded either by a unipolar signature sequence of the modified PN code if the data bit is 1 or its complement if the

data bit is 0.

When the ONU #0 is assigned to modify the PN code sequences, $C_0 = (1, 1, 1, 0, 0, 1, 0, 0)$, the FBGs are placed with central wavelengths of $\lambda_0, \lambda_1, \lambda_2$, and λ_5 . When the ONU #0 transmits the data bit 1, the encoded optical signals are generated with the reflected optical signals $\lambda_0, \lambda_1, \lambda_2$, and λ_5 at the FBG encoder #0 by using an optical switch. While the ONU #0 transmits the data bit 0, the encoded optical signals are generated with the transmitted optical signals $\lambda_3, \lambda_4, \lambda_6$, and λ_7 at the FBG encoder #0 by using an optical switch. As an $n \times 1$ optical coupler connects an OLT with n FBG encoders, each FBG encoder at the ONU transmits its spectral encoded signal to all FBG decoders at the OLT.

The FBG decoder uses two photo diodes to eliminate MAI and improve the bit error rate (BER) compared to the conventional decoder with a unipolar capacity at the same signal to interference plus noise ratio (SINR). The transmitted light field and the reflected light field complement each other at the FBGs. Out of the received signal spectra, the transmitted light field is detected by the upper photo diode PD2 and the reflected light field is directed to the lower photo diode PD1 by a circulator and detected. The two output current signals are subtracted and integrated at the low pass filter (LPF), and the desired data are regenerated by a discriminator.

III. Theoretical Analysis of SINR and BER

While the CDMA decoding pattern at the FBG decoder matches the received signal spectrum from the same pattern of the FBG encoder, the upper photo diode PD2 detects the signal when the data bit is 0 and the lower photo diode PD1 detects the signal when the data bit is 1, and the complement photo diode does not detect any signal. The subtracted current of the two photo diodes for the desired signal of ONU #j is given by

$$i_{s_j} = i_1 - i_2 = \alpha L \sum_{k=0}^{n-1} p(k) C_j(k), \quad \text{for a data bit of 1,} \quad (1)$$

$$i_{s_j} = i_1 - i_2 = -\alpha L \sum_{k=0}^{n-1} p(k) \bar{C}_j(k), \quad \text{for a data bit of 0,} \quad (2)$$

where $p_0 = p_1 = \dots = p_{M-1} = (p(0), p(1), \dots, p(n-1))$ are the output powers of the broadband light source for all users, and α, L, M , and n are the responsivity of the photo diode, the optical attenuation ratio between the light source and the photo diode, the number of connected ONUs, and the code length, respectively. In addition, $p(k)$ reflects the spectral shape of the broadband source, and we assume it follows a Gaussian distribution. The transmitter optical power P_s is defined as the summation of $p(0), p(1), \dots, p(n-1)$. As an

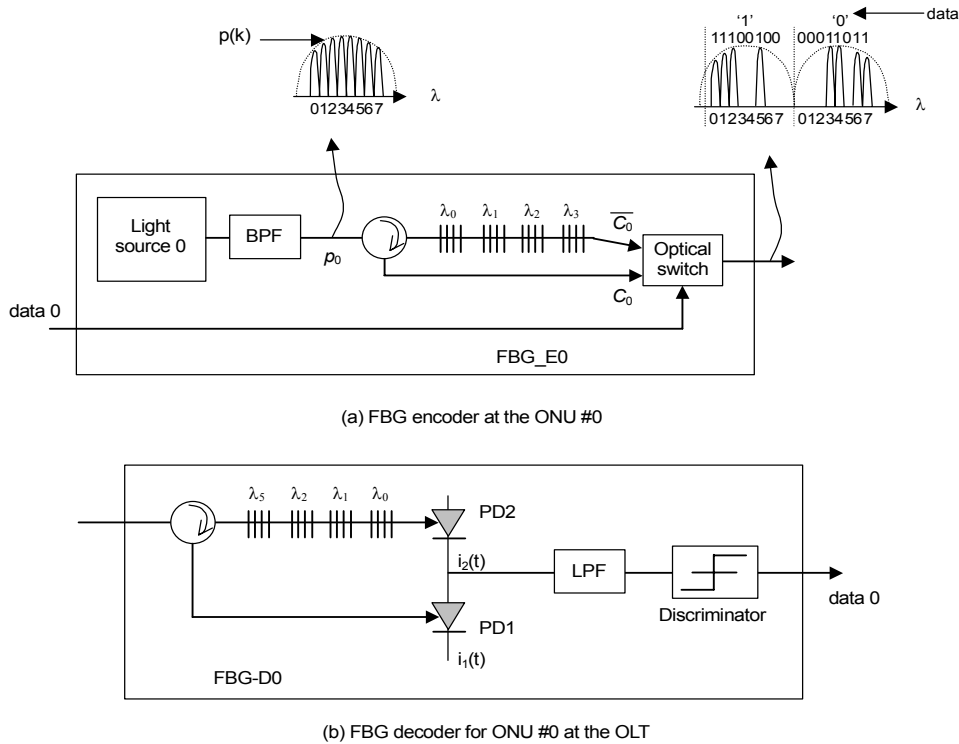


Fig. 3. The schematic diagram of the FBG encoder and FBG decoder.

ideal case, we assume the optical loss is $1/n^2$ where we consider the splitting losses of two optical couplers but not the insertion losses of the optical couplers, FBGs, optical switch, and circulators.

While the CDMA coding pattern at the FBG decoder mismatches the signal spectrum received from a different pattern of the FBG encoder, the upper photo diode PD2 and the lower photo diode PD1 detect the signals simultaneously. The total current is obtained by summing all the interference components (from ONU #i) contributed to the ONU #j with respect to i ($i \neq j$), each of which is calculated by the difference between the detected currents at the PD2 and PD1. The current subtracted from the two photo diodes for the interference at the decoder #j is given by

$$i_{I_{ij}} = i_1 - i_2 = \alpha L \sum_{k=0}^{n-1} p(k) C_i(k) [C_j(k) - \bar{C}_j(k)],$$

for a data bit of 1, and (3)

$$i_{I_{ij}} = i_1 - i_2 = \alpha L \sum_{k=0}^{n-1} p(k) \bar{C}_i(k) [C_j(k) - \bar{C}_j(k)],$$

for a data bit of 0. (4)

When there are spectrally flat light sources, the interference currents are zero because $\sum_{k=0}^{n-1} C_i(k) [C_j(k) - \bar{C}_j(k)] = 0$.

However, because the general light sources have nonflat spectrum distribution, the interference current will be detected. In this case, the desired signal power S and the interference power I at the output of the LPF are given by

$$S = i_{s_j}^2 \quad (5)$$

and

$$I = \sum_{i=0, j \neq i}^{M-1} i_{I_{ij}}^2, \quad (6)$$

respectively.

The additive noise power is composed of the relative intensity noise power, shot noise power, receiver thermal noise power, and optical amplifier noise powers. Here we ignore the optical signal beat noise power because it can be suppressed by the subtraction process after detection at the two photo diodes [13]. The noise power is given by

$$N = N_{RIN} + N_{SHOT} + N_{TH} + N_{SSP} + N_{SPSP}. \quad (7)$$

Each noise power is given by

$$N_{RIN} = \xi_{RIN} i_{s_j}^2 D_r, \quad (8)$$

$$N_{SHOT} = 2e\alpha(P_{r_j} + N_{sp}W)D_r, \quad (9)$$

$$N_{TH} = \frac{8k_B T}{R_L} D_r, \quad (10)$$

$$N_{ssp} = 4\alpha^2 N_{sp} \frac{P_{r_j}}{2} D_r, \quad (11)$$

$$N_{spsp} = 2\alpha^2 N_{sp}^2 W, \quad (12)$$

$$P_{r_j} = L \sum_{i=0}^M \sum_{k=0}^{n-1} p(k) C_i(k) C_j(k), \quad (13)$$

where $e, \xi_{RIN}, k_B, T, R_L, D_r, W$, and P_{r_j} are the electric charge, power spectral density (PSD) of the relative intensity noise, Boltzmann constant, noise temperature, load resistance, data bit rate, optical filtering bandwidth, and receiving optical power in one PD of the j-th decoder, respectively. The PSDs of the amplified spontaneous emission N_{sp} is given by

$$N_{sp} = \frac{\eta_{sp}}{\eta_a} \frac{G-1}{G} h\nu, \quad (14)$$

where $\eta_{sp}, \eta_a, h\nu$ and G are the spontaneous emission factor, quantum efficiency, photon energy, and gain of the optical amplifier, respectively.

Thus, the signal to interference ratio (SIR), the signal to noise ratio (SNR) and the SINR are given by

$$SIR = S/I, \quad (15)$$

$$SNR = S/N, \quad (16)$$

$$SINR = S/(N+I), \quad (17)$$

respectively.

The power component at the output of the LPF is the sum of the desired signal power, interference power, and noise power. We considered a system in which the interference from one ONU is not significantly stronger than that from any other ONU because optical fiber has a small transmission loss. The interference is a random variable and independent in each ONU for the large simultaneous ONU number and code length. Hence, we can consider that the MAI and noise at the output of LPF is a zero-mean Gaussian distributed function [10], [17]. Assuming that the data bits 1 and 0 are transmitted with a probability of 0.5, the BER is given by

$$BER = \frac{1}{4} \operatorname{erfc}\left(\frac{I_1 - I_D}{\sqrt{2}\sigma_1}\right) + \frac{1}{4} \operatorname{erfc}\left(\frac{I_D - I_0}{\sqrt{2}\sigma_0}\right), \quad (18)$$

where I_1 and I_0 are the mean currents for the data bit 1 and 0, respectively, and I_D is the threshold current. Additionally, σ_0 and σ_1 are the current standard deviation of the interference and the noise current for the data bits 1 and 0, respectively [14]. As I_0 and σ_0 are equal to $-I_1$ and σ_1 , respectively, in the proposed system with a bipolar capacity, and I_D is 0, the BER is expressed as

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{I_1}{\sqrt{2}\sigma_1}\right) = \frac{1}{2} \operatorname{erfc}\left(\sqrt{SINR/2}\right). \quad (19)$$

By contrast, the BER of the conventional on-off shift keying with only a unipolar capacity [15] can be written as [18]

$$BER = \frac{1}{2} \operatorname{erfc}\left(\sqrt{SINR/8}\right). \quad (20)$$

Thus, the proposed system can easily achieve the same performance at a lower SINR by 6 dB than that of the conventional system with a unipolar capacity.

IV. Numerical Results and Discussions

In this section, we discuss some numerical results for the proposed OCDMA system. Table 2 shows the parameters used for the numerical calculations. Here, the spectral power distortion ratio of the broadband light source with Gaussian distribution is defined as the ratio of the difference between the maximum and minimum output power to the maximum output power of the broadband light source as follows:

$$\text{Power distortion ratio} \equiv \frac{p(n/2-1) - p(0)}{p(n/2-1)} \times 100(\%). \quad (21)$$

Figure 4 shows the SIR and SINR curves as a function of the spectral power distortion ratio of the broadband light source for code lengths of 32 and 128 and 0 dBm total optical power of the broadband light source. The number of connected ONUs is fewer than the code length by one. The SIR is the same regardless of the number of connected ONUs. In the case of a spectral power distortion ratio of 0, the SIR is infinite, namely the MAI is free for the spectrally flat broadband light source. When the spectral power distortion is limited to within 20%, an SIR of 20 dB can be guaranteed. Considering the noise power, the SINR is more dominated by the SNR than the SIR when the spectral power distortion ratio is small. The SINR is dominated by the thermal noise when the number of connected ONUs

Table 2. Parameters used for the numerical calculations.

Parameters	Values
Responsivity of PD, α	0.8 A/W
PSD of relative intensity noise, ξ_{RIN}	-152 dB/Hz
Load resistance, R_L	50 Ω
Data bit rate, D_r	155.52 Mb/s
Noise temperature, T	300 K
Optical filtering bandwidth, W	1 THz
Spontaneous emission factor of OA, η_{sp}	2.0
Quantum efficiency of OA, η_a	0.5
Optical path loss	$1/n^2$
Optical amplifier gain, G	n
Optical attenuation ratio, L	$n \times 1/n^2$

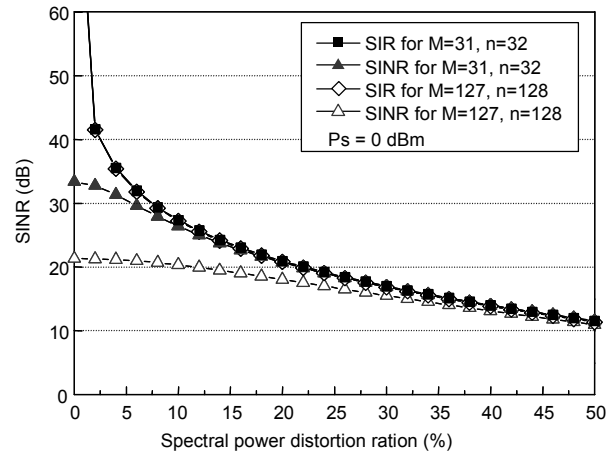


Fig. 4. SIR and SINR curves as a function of spectral power distortion ratio.

increases, because the attenuation ratio increases in proportion to the ONU number. Thus, the SINR is not affected by the spectral power distortion when the number of connected ONUs is 127 with a code length of 128.

Figure 5 shows the BER of the recovered signal as a function of the spectral power distortion ratio. The thermal noise deteriorates the BER when the number of connected ONUs is large. The allowed tolerances of the spectral power distortion ratio are 34% and 28% with a BER of 10^{-9} when the numbers of connected ONUs are 31 and 127 with code lengths of 32 and 128, respectively. The BERs with the proposed bipolar OCDMA are dramatically improved over the conventional unipolar OCDMA systems [12].

Figure 6 shows the relationship among the SIR, SINR, and the ONU number for spectral power distortion ratios of 0%

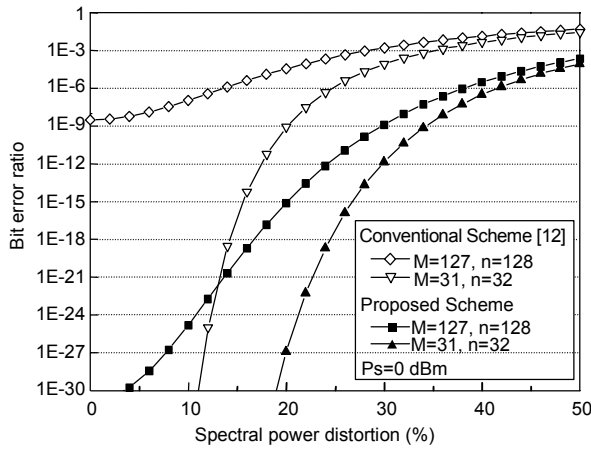


Fig. 5. BER curves as a function of spectral power distortion ratio.

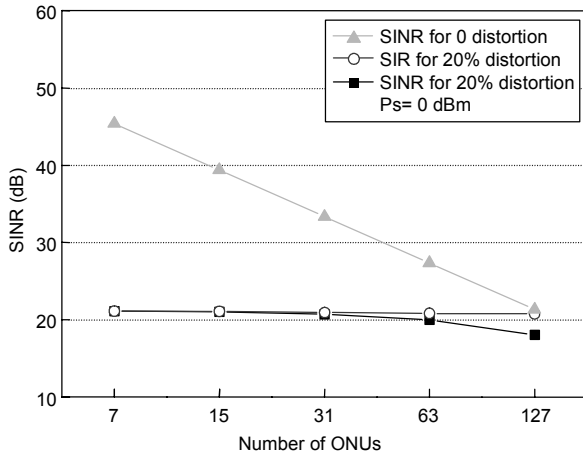


Fig. 6. Relationship among the SIR, SINR, and the ONU number for spectral power distortion ratios of 0 and 20%.

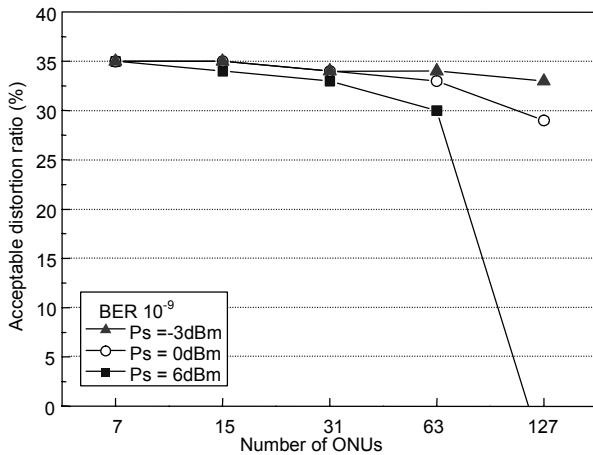


Fig. 7. Interrelationship between the simultaneous ONU number and the spectral power distortion ratio at a BER of 10^{-9} .

and 20%. Here, the code lengths are the same as the ONU numbers plus 1. The SIR is constant regardless of the ONU

number and is infinite for spectral power distortion ratios of 0 %.

Figure 7 shows the interrelationship between a simultaneous ONU number and the spectral power distortion ratio of the broadband light source with various transmitted optical peak powers at a BER of 10^{-9} . Here, the code lengths are the same as the ONU numbers plus 1. The spectral power distortion should be limited to within 33% to keep the simultaneous user number constant at a BER of 10^{-9} when the transmitted optical peak power is 6 dBm. When the transmitted optical peak power is smaller than 6 dBm, the spectral power distortion should be strictly depressed because of the thermal noise as the simultaneous ONU number connected to the proposed system increases with a BER of 10^{-9} .

V. Conclusion

We have proposed an OCDMA scheme to reduce multiple access interference (MAI) and enhance performance for optical subscriber access networks using modified PN coded FBGs with a bipolar OCDMA decoder. Through the bipolar OCDMA decoder and modified PN codes, MAI among ONUs can be eliminated when there is no spectral power distortion. As the data are encoded by either a unipolar signature sequence of the modified PN code or its complement according to whether the data bit is 1 or 0, the BER can be improved under the same SINR compared with the on-off shift keying-based OCDMA system. We have also taken account of the spectral power distortion effects of the broadband light source.

We showed that the spectral power distortion should be limited to within 33 % to keep the simultaneous user number constant at a BER of 10^{-9} when the total transmitted optical power is 6 dBm. When the transmitted optical power is small, the spectral power distortion ratio should be strictly depressed because of the thermal noise.

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