Performance of Bipolar Optical Spectral Encoding CDMA with Modified PN Codes

Sun Hyok Chang, Bong Kyu Kim, Heuk Park, Won Kyoung Lee, and Kwangjoon Kim

ABSTRACT—Experimental demonstration of bipolar spectral encoding code-division multiple-access with modified pseudorandom noise codes is presented. Bipolar spectral encoding is achieved with an erbium-doped fiber amplifier amplified spontaneous emission source and arrayed waveguide gratings. The bit-error rate performance of 1.25 Gbps signal transmission over 80 km single mode fiber is measured in a multiple-user environment.

Keywords—Access network, optical code-division multiple-access (CDMA), optical fiber communications.

I. Introduction

Optical code-division multiple-access (CDMA) offers several potential benefits for broadband multiple-access networks. These include the following: format-independent physical layer security, decentralized network control, enhanced reliability and survivability, and uncoordinated access due to contention-free property [1], [2]. The implementation of various optical CDMA schemes has been reported, such as time spreading CDMA, coherent coding CDMA, spectral encoding CDMA, and two-dimensional CDMA.

Spectral encoding CDMA has a number of advantages. Temporal synchronization is not required, the number of subscribers in a network can be large, and the encoder may use a simple broadband spectral source instead of a short pulse laser. Moreover, bipolar capacity can be obtained by pseudorandom noise (PN) codes or Walsh codes [3], [4]. Recently, modified PN code was proposed where the stuffing bit of '0' is inserted at the end of each PN code making the number of '1' always equal to the number of '0' in a code to reduce the multiple access interference [5], [6].

In this letter, we measured the BER performance of bipolar spectral encoding CDMA with modified PN codes. Spectral encoding was achieved with an erbium-doped fiber amplifier (EDFA) amplified spontaneous emission (ASE) source and arrayed waveguide gratings (AWGs). AWG could replace the bulk grating [3] or the fiber grating [5] in spectral encoding. The performance of optical CDMA channel transmission over 80 km single mode fiber (SMF) was also demonstrated in a multiple-user environment.

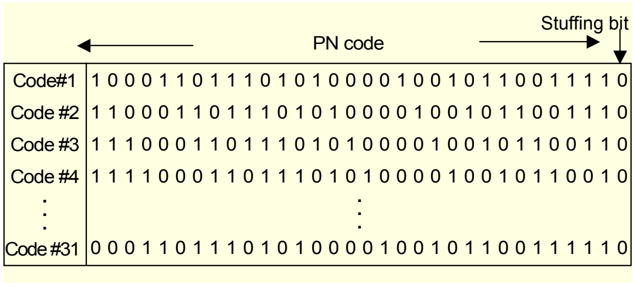

Fig. 1. Modified PN codes of code length 32.

II. Experimental Configuration

Modified PN codes of code length 32 are shown in Fig. 1. The stuffing bit of "0" was inserted at the end of a PN code sequence. The modified PN codes could be easily constructed by shifting and stuffing a bit from well known PN codes.

Figure 2 shows the experimental set-up for bipolar spectral encoding CDMA. C-band EDFA ASE was employed as a broadband spectral source. An AWG demultiplexer was used to divide the broadband source into 32 spectral chips. Following

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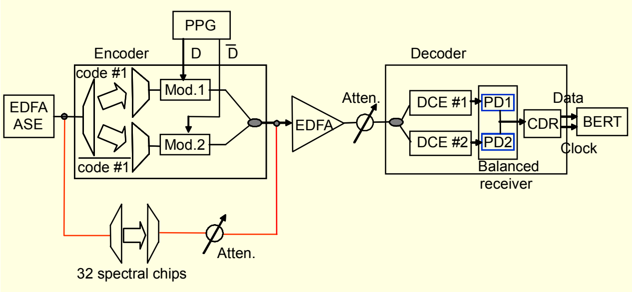

Fig. 2. Experimental set-up for bipolar spectral encoding CDMA.

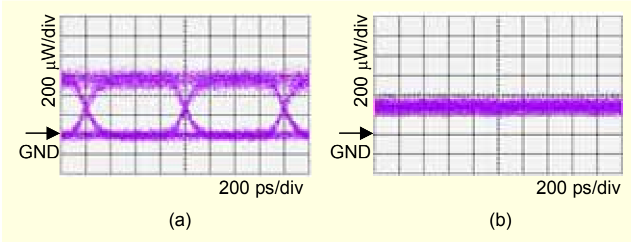

Fig. 4. Eye diagram of DCE #1 output when DCE #1 was coded with (a) Code#1 and (b) Code#2. Receiver bandwidth was 7.5 GHz for the eye measurement.

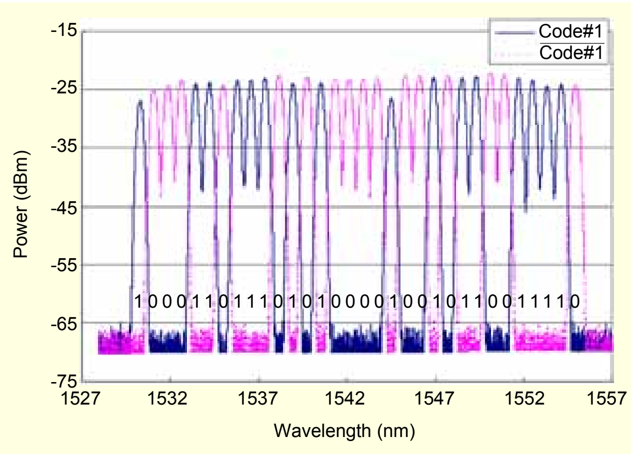

Fig. 3. Optical spectrum of encoder output coded with Code#1 and $\overline{\text{Code\#1}}$. Resolution bandwidth was 0.1 nm. The code sequence of Code#1 is depicted.

Code#1 in Fig. 1, 16 spectral chips were assigned to an AWG multiplexer (mux). The remaining 16 spectral chips were assigned to the other AWG multiplexer to make complementary Code#1 ($\overline{\text{Code\#1}}$). The center wavelength of the chips was between 1530.33 and 1554.94 nm with 100 GHz spacing and 3 dB bandwidth of each chip was approximately 40 GHz. The spectrally encoded output of each mux was modulated by an $LiNbO_3$ modulator with 1.25 Gbps NRZ 2^{31}-1 PRBS signal; Code#1 was modulated by the data signal (D) and $\overline{\text{Code\#1}}$ was modulated by the complementary data signal ($\overline{\text{D}}$) of a pulse pattern generator (PPG). The two modulated optical outputs were synchronized to each other by adjusting the electrical delay of the data signal (D) and combined by a 3-dB fiber coupler. Therefore, the NRZ signal patterns complemented each other in time and the optical output of the encoder was continuous wave (CW)-like.

Figure 3 shows the optical spectrum of the encoder output. The peak power variation of the spectral chips was smaller than 4 dB.

At the decoder, the optical power was split by a 3-dB fiber coupler and directed to each dynamic channel equalizer (DCE). The employed DCEs sliced the optical spectrum and attenuated specific channel up to 40 dB before recombining them. DCEs were used for the decoding instead of AWGs because DCEs could be controlled easily to provide any code sequence. The center wavelengths of the DCE channels were the same as those of the AWGs in the encoder. The 0.2 dB bandwidth of DCE channels was approximately 50 GHz, wide enough to pass the spectral chips with little influence. DCE #1 was set with Code#1 and DCE #2 was set with $\overline{\text{Code\#1}}$.

Figure 4(a) shows the eye diagram of the DCE #1 output presenting a clear eye opening. The output of DCE #2 was nearly the same as in Fig. 4(a). However, when DCE #1 was set with Code#2 and DCE #2 was set with $\overline{\text{Code\#2}}$ in Fig. 1, the output of each DCE was CW-like as shown in Fig. 4(b). The coded signal was recovered only when the code was matched at the decoder due to the orthogonality of the modified PN code.

The optical output of each DCE was directed to each input port of a balanced receiver and converted to electrical signals. The 3 dB bandwidth of the balanced receiver was approximately 800 MHz. The clock and data signal from the CDR (clock and data recovery) board was used to measure the BER performance of the spectrally encoded signal. The EDFA in Fig. 2 was used to amplify the signals, and the experiments confirmed that EDFA has no significant effects on the BER performance of the signals.

III. BER Performance in Multiple-User Environments

In multiple-user environments, each receiver in a network will receive all of the signals from all active encoders in the network [6]. While the matching channel signal is recovered by a decoder, all other unmatched channel signals play the role of noise which can produce multiple access interference (MAI) noise as shown in Fig. 4.

In order to emulate the condition of multiple channels, 32 spectral chips of ASE were produced by combining two AWGs and added to the encoder output with a 3-dB coupler as shown in Fig. 2. Its optical intensity relative to the encoder output was manipulated by the attenuator to simulate a multiple-user

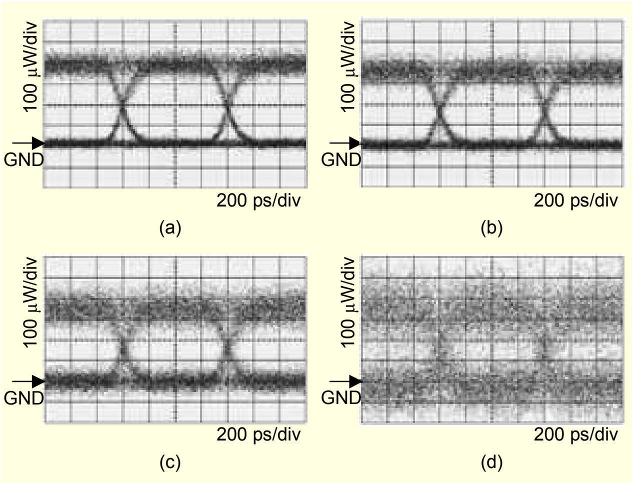

Fig. 5. Eye diagrams of DCE #1 outputs under the conditions of (a) one channel, (b) two channels, (c) four channels, and (d) eight channels. Receiver bandwidth was 7.5 GHz for the eye measurement.

environment in a network. If we assume that all of the signals would have the same optical intensity at a receiver, the ratio can be directly translated as the number of simultaneous users in the network. The decoder was set with Code#1 and Code#1 that was the same code as the encoder.

Figure 5(a) shows the eye diagram of the DCE #1 output when there was no other user. Figure 5(b) shows the case of two simultaneous users, in which the noise intensity is the same as the encoder output intensity. The noise intensity became three times stronger than the encoder output intensity in Fig. 5(c), simulating four simultaneous users. Figure 5(d) shows the case of eight simultaneous users. The MAI noise degrades the quality of the signal.

Figure 6 illustrates the measured BER curves with various numbers of simultaneous users when the data rate was 1.25 Gbps per user. The solid symbols are back-to-back cases and the open symbols are 80 km SMF transmission, with additional EDFA equipped with DCF to compensate the dispersion of the SMF. The measured received power was the sum of two input powers of a balanced receiver. The slope of the BER curve had a floor of approximately 1×10^{-7} in the case of eight channels. No significant power penalty was observed after 80 km SMF transmission.

Because the signal was spectrally encoded, it could be modulated in time by any amplitude modulation format such as NRZ. Therefore, the signal was easily transmitted over a long length of fiber and broadband signal transmission was possible. We believe this is the first time that the transmission of optical CDMA signal over 80 km SMF has been demonstrated.

Transmission performance was limited by the MAI noise in multiple-user environments. Because an ASE source was used

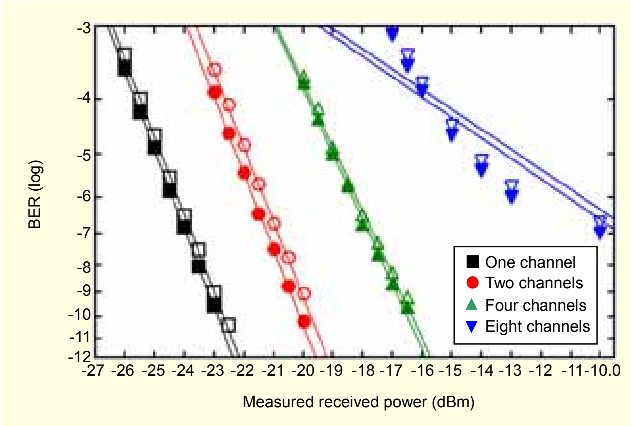

Fig. 6. BER performance with measured received power of balanced receiver when the number of channels was changed. BER data depicted with hollow symbols were the results after 80 km SMF transmission.

in the experiments, spontaneous-spontaneous beat noise would have been the main source of the MAI. Since MAI can be further suppressed by simply extending the effective optical bandwidth of spectral encoding [7], more than ten simultaneous users could be accommodated in a network operated in 1.25 Gbps over 80 km SMF. The effective optical bandwidth can be increased by increasing the bandwidth of each spectral chip or by increasing the number of spectral chips.

IV. Conclusion

In this letter, we measured the BER performance of bipolar spectral encoding CDMA with modified PN code. The bipolar spectral encoding was achieved with an EDFA ASE source and AWGs. The transmission performance in a multiple-user environment was also demonstrated to show the effects of MAI noise. The spectrally encoded signals were transmitted over 80 km SMF. This demonstrates that an optical spectral encoding CDMA technique can be an alternative in multiple access networks.

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