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Authors
Cong, Wei
Yang, Chunxin
Scott, Ryan P
et al.

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Demonstration of 160- and 320-Gb/s SPECTS O-CDMA Network Testbeds

Wei Cong, Chunxin Yang, Ryan P. Scott, Vincent J. Hernandez, Nicolas K. Fontaine, Brian H. Kolner, *Senior Member, IEEE*, Jonathan P. Heritage, *Fellow, IEEE*, and S. J. Ben Yoo, *Senior Member, IEEE*

***Abstract*—This letter presents a high-capacity optical code-division multiple-access (O-CDMA) network testbed based on the spectral phase-encoded time-spreading technique. Two 10-Gb/s/user O-CDMA network architectures (time-slotted and time-slotted polarization multiplexed) are investigated. The first O-CDMA network testbed architecture utilizes eight encoders and a decoder to produce 16 users equally distributed in two time slots while the second architecture evenly distributes 32 users in two time slots and two polarizations. The 16-user testbed achieved error-free performance. The 32-user testbed obtained bit-error rates below 10^{-8} without using forward-error-correction techniques.**

***Index Terms*—Multiaccess communication, optical code-division multiple-access (O-CDMA), optical fiber communications.**

I. Introduction

DRIVEN by the rapid increase of communication bandwidth demands, multiplexing has become an essential approach in both wireless radio and optical networks. Wavelength-division multiplexing (WDM) and time-division multiplexing (TDM) are widely used in metropolitan and core optical fiber networks, while code-division multiplexing (CDM) dominates in wireless networks. CDM is normally used as an access technology, namely code-division multiple-access (CDMA), in wireless networks. However, there is still no prevailing technique for optical access networks. Recently, optical CDMA (O-CDMA) has been investigated as a promising candidate for use in local access networks because of its advantages in simplicity, flexibility, scalability, and enhanced security [1]. Various O-CDMA network experiments have been reported utilizing different light sources, coding schemes, and detection methods [2]–[4]. The O-CDMA network testbed demonstrated in this letter uses a spectral phase-encoded time-spreading (SPECTS) technique. In binary-phase SPECTS O-CDMA, a unique phase code (0 or π) is impressed on the spectrum of the ultrashort signal pulses for each user, and hence spreads the pulses in time. At the decoder, signal pulses from the desired user can be recovered by using the conjugate phase code.

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W. Cong, C. Yang, R. P. Scott, and B. H. Kolner are with the Department of Applied Science, University of California, Davis, Davis, CA 95616 USA (e-mail: wcong@ucdavis.edu).

V. J. Hernandez, N. K. Fontaine, J. P. Heritage, and S. J. B. Yoo are with the Department of Electrical and Computer Engineering, University of California, Davis, Davis, CA 95616 USA (e-mail: yoo@ece.ucdavis.edu).

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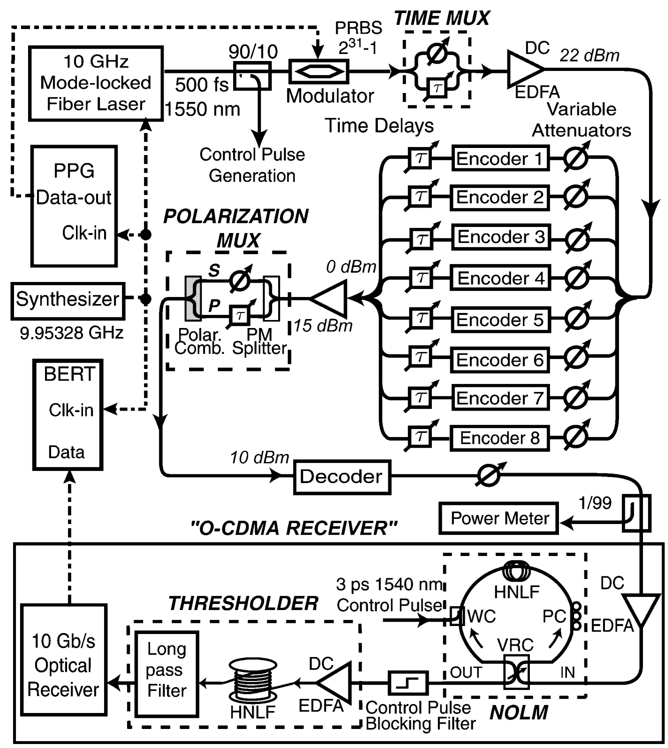

Fig. 1 The 16- and 32-user SPECTS O-CDMA network testbed incorporating both time-slotting (16- and 32-user) and polarization multiplexing (32-user only).

To increase spectral efficiency, we have previously demonstrated time-slotted SPECTS O-CDMA network testbeds [5]. In the testbed presented here, we incorporate both time slotting and polarization multiplexing. In addition to an O-CDMA phase code, each user is assigned a particular time slot and a polarization direction (S or P). Different users in different time slots and/or different polarizations can share the same code. The maximum number of users supported by the testbed is eight per time slot per polarization. Based on this, bit-error-rate (BER) statistics are measured on the testbed for up to 16 users with only time slotting, and for up to 32 users with both time slotting and polarization multiplexing.

II. Testbed Description

Fig. 1 shows the details of the physical layout of the O-CDMA network testbed. The O-CDMA encoders and decoder are fiber-pigtailed, zero-dispersion pulse shapers using reflective-mode liquid crystal spatial light phase modulators (LC-SLPMs) in the Fourier plane. Circulators separate the output signal from the input signal of the pulse shapers. The insertion losses of these pulse shapers are typically ~8 dB (includes 3.5-dB loss from circulators). The O-CDMA phase codes are added on the user signals in the spectral domain by LC-SLPMs. In the testbed, the mode-locked fiber laser source generates a 9.95328-GHz (OC-192 rate), 0.5-ps optical pulse train with center wavelength at 1550 nm. The pulse train is modulated with a $2^{31} - 1$ bit pseudorandom bit sequence (PRBS), and time-multiplexed into two time slots, each 50 ps wide. In the 16-user experiment, the time-multiplexed signal is amplified by a dispersion-compensated erbium-doped fiber amplifier (DC-EDFA), then split into eight branches, each supplying an encoder. Each encoder branch contains variable time delays, which ensure that all users transmit synchronously within 0.5 ps. The time delays also apply different relative bit shifts to the PRBS, decorrelating the pattern between users. Hadamard Walsh codes 5, 6, 16, 28, 34, 40, 52, and 54 are impressed upon Encoders 1–8 for minimum interference between users [6]. The combined encoded signal stream of 16 users (in two time slots) is sent to the decoder after amplification. The output of the decoder passes through a nonlinear optical loop mirror (NOLM) for time-demultiplexing. The temporal gate of the NOLM is 3 ps wide and is timed to arrive at the center of one time slot [5]. Although the control pulse is currently derived from the mode-locked laser, recent demonstrations of O-CDMA clock recovery [7] suggest the feasibility of generating the control pulse locally at the receiver. A highly nonlinear fiber (HNLF)-based thresholder is used after the NOLM to further suppress the remaining multiuser interference (MUI). The output of the thresholder is converted into an electronic signal by an optical receiver and then sent to the BER tester (BERT).

The testbed structure for the 32-user experiment is similar to the 16-user experiment, but with the addition of a polarization multiplexer module after the encoders (Fig. 1). In the polarization-multiplexer, the 16-user time-slotted signal stream is first split into two arms then recombined by a polarization beam combiner. The two perpendicular polarization components (S and P) are launched into the slow and fast axis of the polarization-maintaining dispersion-shifted fiber (PM-DSF), respectively. The combined signal includes a total of 32 users in two time slots with two polarizations. Both the time and polarization multiplexers decorrelate the data in adjacent time slots and different polarizations since they have differential delays (between arms) of tens of bits. Signals from either S or P polarization may be selected at the output of the decoder. The PM-DSF circulator in front of the decoding pulse shaper also acts as a linear polarizer (26-dB extinction ratio). Moreover, the grating in the pulse shaper provides additional 20 dB to the extinction ratio (two passes). The combination of the circulator and grating works as a polarization demultiplexer.

III. Results and Discussion

Fig. 2(a) and (b) show the combined signal from 16 users in two time slots measured with a cross-correlator before, and after the NOLM time gate. Fig. 2(c) shows a MATLAB simulation of the combined signals. The close match with the experimental result in Fig. 2(a) indicates good encoding–decoding implementation and system alignment including uniform time-slot allocation. In Fig. 2(a), the high peak in the center of each time slot is from a correctly decoded user. As shown in Fig. 2(b), the 3-ps-wide NOLM time gate passes the center of Time Slot

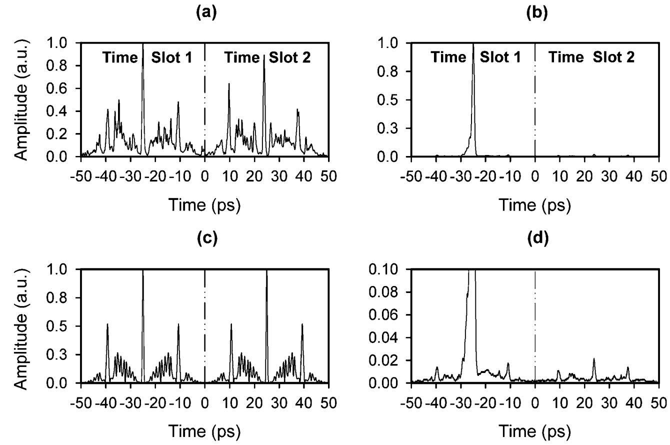

Fig. 2 Cross-correlation traces of the 16 time-slotted O-CDMA users (0.5-ps reference pulse). (a) Measured at the input to NOLM. (b) Measured at the output of NOLM. (c) Simulation of (a) with MATLAB. (d) Scaled view of (b) showing residual interfering signals.

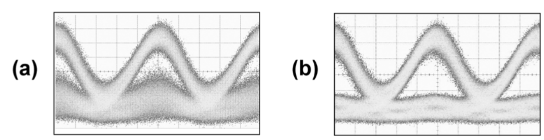

Fig. 3 Eye diagrams for 16 time-slotted users taken at the output of (a) the NOLM and (b) the output of the thresholder.

1 and blocks most of the MUI. However, the HNLF thresholder is still required to suppress the remaining MUI, which is apparent in the scaled view of the bottom of the correlation trace in Fig. 2(d). The NOLM, the HNLF thresholder, and the optical receiver are defined as the "O-CDMA Receiver" in the testbed in Fig. 1. The necessity of using the HNLF thresholder in the O-CDMA receiver is demonstrated in Fig. 3, which shows the eye diagrams of the intended user in the 16-user experiments. Without the HNLF thresholder, the zero level of the eye blurs because of the MUI shown in Fig. 2(d). The BER levels corresponding to Fig. 3(a) and (b) are $\sim 10^{-5}$ and $< 10^{-11}$, respectively.

The BER performance of the 16-user time-slotted SPECTS O-CDMA network testbed is shown in Fig. 4. The BER curve plots reference optical power *per user* measured prior to the O-CDMA receiver module in Fig. 1. The back-to-back curve is taken while sending the time-mutiplexed signal directly into the O-CDMA receiver. In the two-user case, Encoder 1 and the decoder are added in the testbed. Each additional encoder adds two more users (one in each time slot) in the testbed. The intended user for BER testing obtains error-free performance (BER $<$ 10^{-11}) for up to 16 total users in the testbed. The last data point in each curve in Fig. 4 indicates the power where error-free performance and eye diagrams are recorded. As shown in Fig. 4, the quality of the eye diagram for 16 users is not noticeably worse than the back-to-back case. The back-to-back and two-to ten-user BER curves are clustered together. But starting with ten users, a 2-dB power penalty (BER $= 10^{-8}$) appears for each additional pair of users. This is caused by the increase of MUI and coherent beat noise between users [8].

Fig. 5 shows the BER results of the 32-user time-slotted polarization-multiplexed SPECTS O-CDMA network testbed.

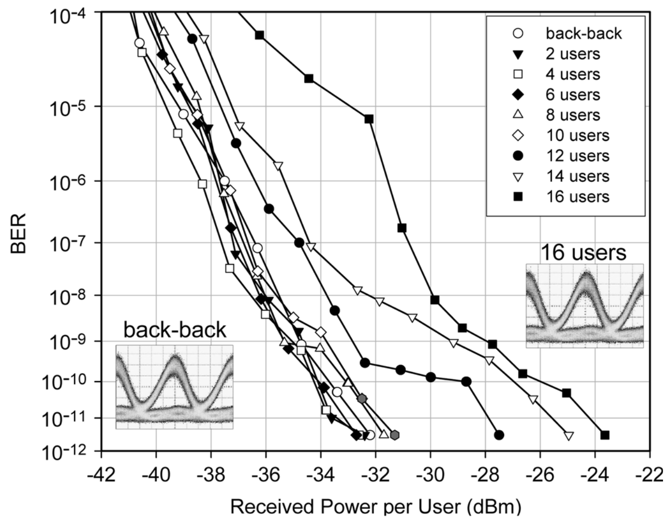

Fig. 4 BER performance of the 16-user (10 Gb/s/user) time-slotted SPECTS O-CDMA network testbed.

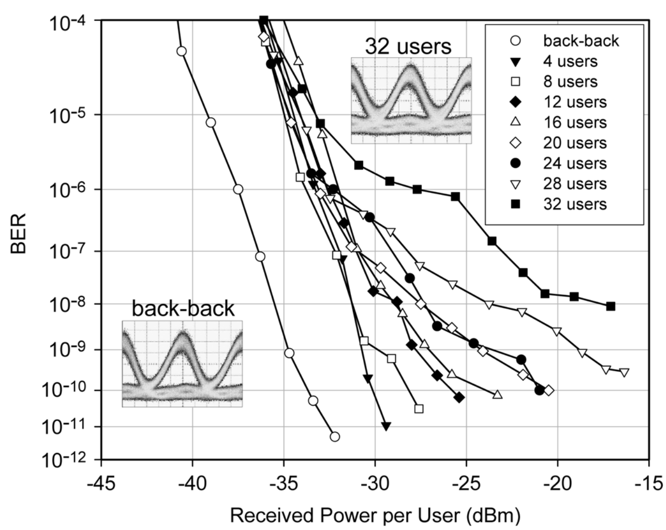

Fig. 5 BER performance of the 32-user (10 Gb/s/user) time-slotted and polarization-multiplexed SPECTS O-CDMA network testbed.

Here, the definition of back-to-back is the same as that in the 16-user experiment. One encoder and decoder pair provides four users, one in each time slot and each polarization. The maximum number of users produced by the eight encoders is 32, evenly distributed in the two time slots and two polarizations. In the BER statistics experiment, the BER of the intended user can reach below 10^{-9} for up to 28 users, and below 10^{-8} for 32 users. Back-to-back and 32-user eye diagrams (taken at the last data point of the corresponding curves) are shown in Fig. 5. There is a 4-dB power penalty ($\mathrm{BER} = 10^{-8}$) between four-user and back-to-back curves in Fig. 5, while there is nearly no power penalty between two-user and back-to-back curves in the 16-user experiment, as shown in Fig. 4. This difference arises from loss, dispersion of the polarization multiplexer, and interference between users on orthogonal polarizations as their extinction ratio degrades. The 4- to 32-user BER curves in Fig. 5 tightly group in the high BER portion and diverge in the lower BER levels. Again, the errors are mainly from MUI and coherent beat noise between user–interferer and interferer–interferer. This issue is more evident with large numbers of users at BER levels below 10^{-6}, and it is also the main challenge to achieving high bandwidth and spectral efficiency in O-CDMA networks [9].

A conservative estimate for the spectral efficiency of the 32-user testbed can be made by using the 10%–90% spectral width, which is $\sim$12 nm, as the system's optical bandwidth. This yields a spectral efficiency of 0.213 bit/s/Hz which is nearly tenfold higher than theoretically predicted for phase encoded coherent O-CDMA [9]. This discrepancy arises from synchronous operation of the testbed with elements not considered in [9], including time and polarization multiplexing, Walsh codes (instead of m-sequences), and time gating. Although some of these increase the system complexity, they act to minimize the interference between synchronous users and, therefore, maximize system throughput.

IV. Conclusion

In this letter, we have demonstrated an SPECTS O-CDMA network testbed with experiments on two types of network architectures. The testbed supports up to 16 users at 10 Gb/s/user in the time-slotted O-CDMA network structure, or 32 users at 10 Gb/s/user in the time-slotted and polarization-multiplexed O-CDMA network structure. Low BER statistics are achieved without need of forward-error correction. This is the highest capacity experimental demonstration of a multiuser access testbed based on the spectral phase coded O-CDMA technique to date.

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