

# Security-Enhanced SPECTS O-CDMA Demonstration Across 150 km Field Fiber

N. K. Fontaine<sup>1</sup>, C. Yang<sup>2</sup>, R. P. Scott<sup>2</sup>, V. J. Hernandez<sup>1</sup>, K. Okamoto<sup>1</sup>, D. L. Harris<sup>3</sup>, J. P. Heritage<sup>1</sup>,  
B. H. Kolner<sup>2</sup>, and S. J. B. Yoo<sup>1</sup>

*Department of Electrical and Computer Engineering<sup>1</sup>, University of California, Davis, 95616*

*Department of Applied Science<sup>2</sup>, University of California, Davis, 95616*

*Advanced Technology Lab<sup>3</sup>, Sprint Nextel, Burlingame, California 94010*

*email: sbyoo@ucdavis.edu*

**Abstract:** We demonstrate security-enhanced, multi-user SPECTS O-CDMA transmission across 150 km of field fiber. The testbed incorporates a fully integrated silica AWG spectral phase encoder/decoder and tunable dispersion slope compensation. Error-free performance is achieved using FEC.

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**OCIS codes:** (060.4250) Networks; (060.4510) Optical communication.

## 1. Introduction

In recent years, the increasing penetration of fiber-to-the-premise (FTTP), and broadband access in general, has renewed interest in optical code-division multiple-access (O-CDMA) technology, due to its potential to provide flexibility and physical layer security to optical access networks [1]. Recent demonstrations of spectral phase encoded time-spreading (SPECTS) O-CDMA, a particular O-CDMA technology, have shown throughputs as high as 320 Gb/s [2,3]. The application of SPECTS O-CDMA has only been considered for local access networks due to the difficulties in transmitting sub-picosecond pulses across long fiber links. The need for higher order broadband dispersion compensation and other link impairments, such as random polarization drifts and polarization mode dispersion (PMD), have limited SPECTS O-CDMA systems to fiber transmission distances of less than 10 km [4]. To address the dispersion problem, this paper presents a novel tunable broadband dispersion slope compensator (DSC) [5]. The system employs a compact, fully-integrated 4×4 encoder/decoder based on polarization-independent, high-density silica arrayed waveguide grating (AWG) technology to achieve high signal-to-multiple access interference (MAI) ratios. With this, we are able to demonstrate multi-user SPECTS O-CDMA using the bright code/dark code (BCDC) modulation format, which has been shown to greatly enhance the security of O-CDMA networks [6]. With forward-error-correction (FEC), we achieve error-free performance of a BCDC-modulated SPECTS O-CDMA system in the presence of an interferer over a record 150 km field fiber link, a first step towards integration of SPECTS O-CDMA into existing metro and wide-access networks.

## 2. SPECTS O-CDMA Encoding and Decoding Technology

In SPECTS O-CDMA, a unique code is applied to the spectral phase of each users' data-modulated pulse train, spreading the time-domain waveform. When all of the users are multiplexed, they share the same wavelength and time space and are indistinguishable from each other in both domains. To detect a user, the receiver applies the conjugate code of the desired user to the data stream. The desired user's spectral phase is equalized, reproducing the short optical pulse, while the incorrectly decoded users' signals (MAI) remain spread in time and minimally interfere. Nonlinear thresholding based on spectral broadening in highly nonlinear fiber then distinguishes the short pulse of the desired user from MAI.

To generate the sub-picosecond pulse train, a stable optical frequency comb generator (OFCG) [7] is compressed in dispersion decreasing fiber to generate over 120 optical comb lines above -20 dBc, spaced at 20 GHz. After modulation, the signal is sent into a fully integrated, polarization independent, silica-based AWG spectral phase encoder (AWGSPE). Independent control of the OFCG center frequency and comb spacing facilitate alignment of the comb to the AWGSPE passbands. The AWGSPE consists of an AWG pair, one AWG to demultiplex an input onto the 64 wavelength channels and the other AWG to multiplex all wavelength channels to a single output. Each wavelength channel contains a phase shifter that is adjusted to be a 0- $\pi$  mapping of a 63-chip  $m$ -sequence. In this experiment, each chip corresponds to a single optical mode. The AWGSPE has four input ports and four output ports, forming four bidirection encoding/decoding channels (i.e., an encoder). Each encoder applies a chip-shifted version of the  $m$ -sequence to the spectral phase of the optical comb.

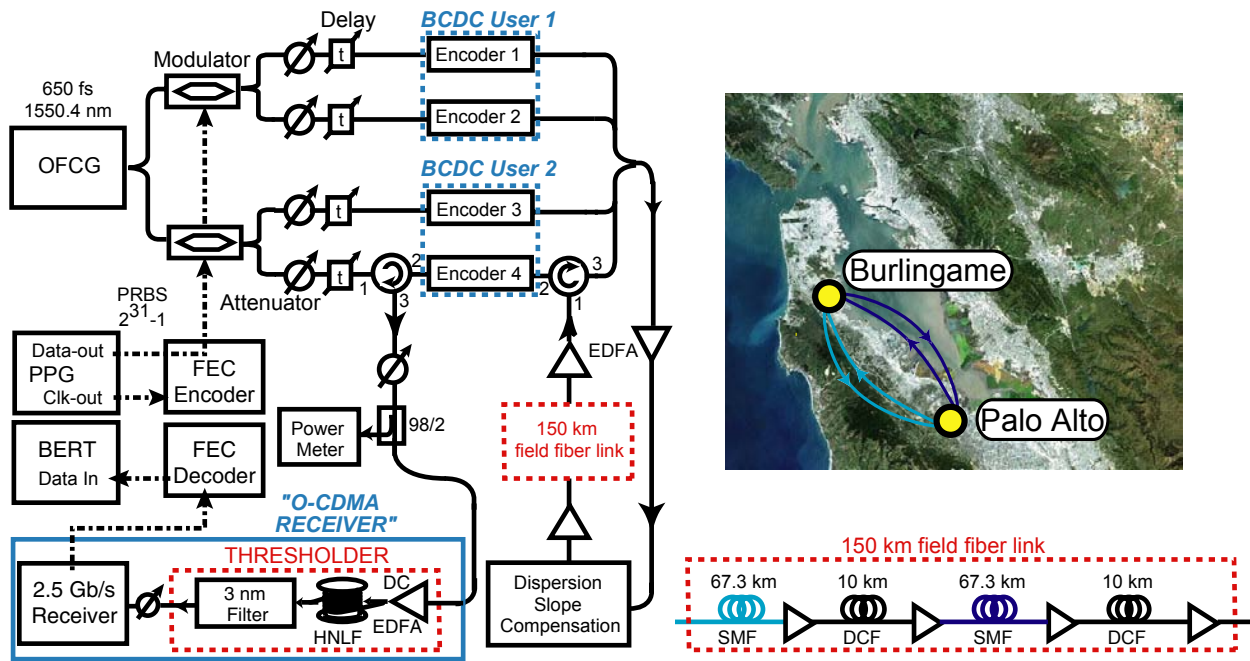


Fig. 1. Experimental setup and field fiber.

### 3. Link Description and Dispersion Compensation

Fig. 1 shows the experimental setup. The output of the OFCG source is split and modulated by two complimentary output Mach-Zehnder modulators (MZM) with a 2.5-Gb/s FEC-encoded pseudo-random bit sequence (PRBS). Each output of the MZM is encoded with an  $m$ -sequence, such that both 1-bits and 0-bits of the PRBS are represented by a unique encoded waveform. The codes applied to the 1-bits and 0-bits are respectively called the bright code (BC) and dark code (DC) of the user, and this modulation scheme makes it much more difficult for an interferer to eavesdrop on an O-CDMA transmission [5]. The BC and DC paths for a particular user are aligned in time and equalized in power before being combined to a single fiber. A total of two users employing BCDC modulation are implemented, and these are combined, amplified, and sent down the 150 km fiber link. The received signal from the link is decoded using the same encoder used for encoding the BC of the desired user. The nonlinear threshold then distinguishes the BC of the desired user from the DC and the interfering user, which remain spread. The resulting optical signal is converted to an electrical signal using a 2.5 Gb/s receiver, FEC decoded, and sent into the bit error rate tester (BERT). Clock recovery of the received signal is provided by the FEC decoder.

Transmission of broadband ( $\sim 10$  nm or 1.2 THz) sub-picosecond pulses across long distances of fiber require careful compensation of both dispersion and dispersion slope. Others have demonstrated sub-picosecond pulse transmission in laboratory fibers using programmable spatial light modulators and specialty fibers [4,8,9]. Our method provides tunable DSC from  $-6$  ps/nm<sup>2</sup> to  $6$  ps/nm<sup>2</sup> across 10 nm of bandwidth using a bulk optics zero-dispersion pulse shaper with a flexible mirror placed at the Fourier plane. The pulse shaper also functions as a 1.3-THz bandpass filter; passing only the encoded signal and suppressing out-of-band noise.

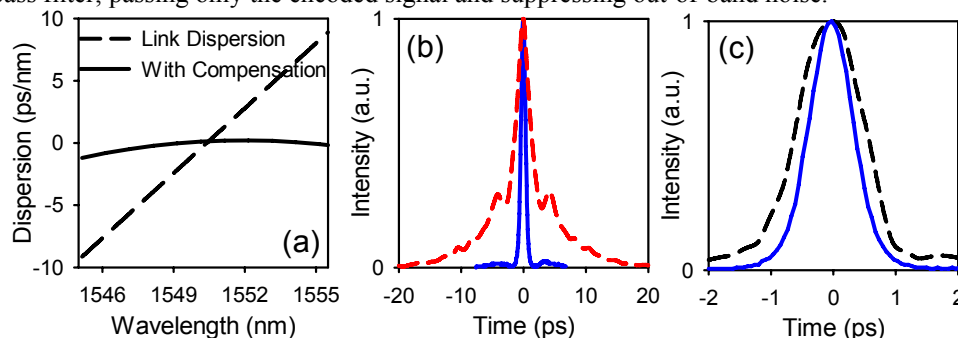


Fig. 2. (a) Link dispersion with, and without, DSC. (b) Autocorrelation of link input without (solid) and with DSC (dashed). (c) Autocorrelation of input pulse (solid) and after 150 km link with DSC (dashed).

We use 150 km of field fiber (circa 1990) that spans between Burlingame, California in Sprint Nextel Advanced Technology Lab, and a point-of-presence in Palo Alto, California (see Fig. 1). The dispersion at 1550.4 nm from each 67.3-km span of SMF is compensated using  $\sim 10$  km of dispersion compensating fiber (DCF) and fine tuned after the link using a tunable dispersion module (Fitel S-DCM) and short lengths of SMF, leaving  $1.71 \text{ ps/nm}^2$  of uncompensated dispersion. The residual dispersion slope (Fig. 2(a)) is enough to spread the pulses to over 20 ps (Fig. 2(b)). Application of the DSC before the link (precompensation) removes the majority of the dispersion slope, and only 0.6 ps/nm peak-to-peak deviation in dispersion remains across the band (see Fig. 2(a)). Fig. 2(c) shows the recovery of an 850-fs pulse from the 630-fs pulse transmitted through the 150 km link. The autocorrelation after the link is mildly asymmetric due to distortions in the polarization state from PMD of the link ( $0.25 \text{ ps}/\sqrt{\text{km}}$ ).

#### 4. Results and Discussion

Fig. 3 shows BER results and corresponding eye diagrams. The received power is measured at the input to the nonlinear thresholder. The center wavelength of the 3-nm filter within the thresholder is optimized for the 2-user case and the delay between the two users is optimized to minimize MAI. Two-user error-free performance is achieved for both back-to-back and 150-km link configurations. The power penalty between the back-to-back and the link is due to degraded optical signal-noise ratio (OSNR) along with random changes in PMD from the field fiber. The 2-user link performance is further degraded by enhanced MAI effects from the link.

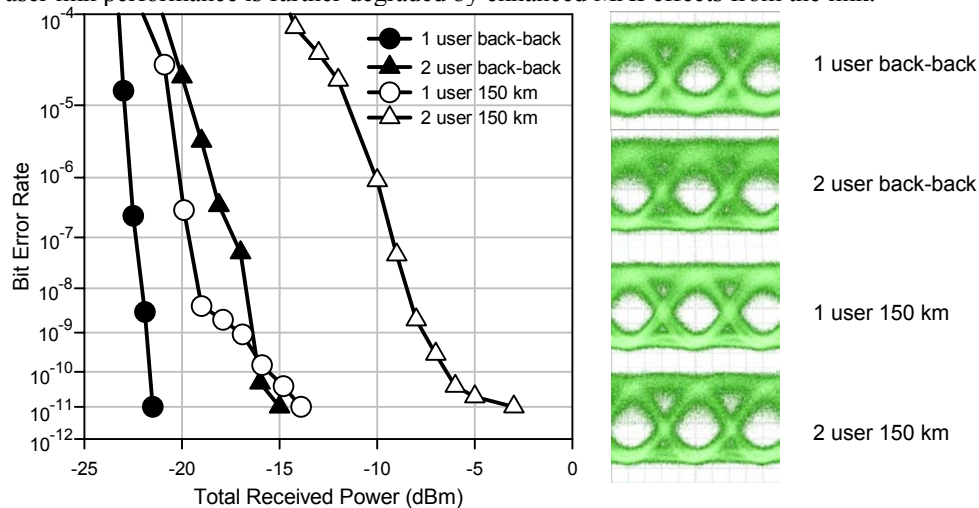


Fig. 3. BER results and eye diagrams.

#### 4. Conclusions

We successfully demonstrate the first 150-km field trial of security-enhanced SPECTS O-CDMA networking using bright-code/dark-code data modulation at 2.5 Gb/s/user incorporating integrated silica AWG encoders.

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This work was supported in part by DARPA and SPAWAR under agreement number N66001-02-18937 and by the AFOSR through the UC Davis Center for Digital Security.