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A 320-Gb/s Capacity (32-User × 10 Gb/s) SPECTS O-CDMA Network Testbed With Enhanced Spectral Efficiency Through Forward Error Correction

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***Abstract*—This paper demonstrates a high-performance optical-code-division-multiple-access (O-CDMA) network testbed using the spectral phase encoded time spreading (SPECTS) method. Through additional time and polarization multiplexing, a total of 32 10-Gb/s users are supported while sharing eight O-CDMA spreading codes. User detection is achieved with time gating and nonlinear thresholding to suppress the multiaccess interference of other users. Incorporation of forward error correction successfully reduces the performance loss imposed by coherent beat interference, resulting in error-free performance ($\mathrm{BER} < 10^{-11}$), significant per-user power penalty reduction, and the elimination of a bit-error-rate noise floor. The testbed also applies bandwidth suppression within the encoders and decoders, yielding a 52% increase in spectral efficiency.**

***Index Terms*—Forward error correction (FEC), multiaccess communication, optical code division multiaccess (O-CDMA), optical fiber communication, phase coding.**

I. INTRODUCTION

CODE DIVISION multiple access (CDMA) is a network access technique through which multiple users access the same bandwidth through encoded transmission. While prominently used in wireless communications to flexibly utilize dynamic system capacity, much interest lies in adopting it in optical communications, where it provides many potential benefits to future local access networks [1]. Under optical CDMA (O-CDMA), all users' transmissions are encoded with a unique signature that renders them indecipherable without a proper decoder. An authorized receiver tunes to the code of the desired transmission to recover the signal, and the signal minimally interferes with other transmissions provided that their codes are orthogonal. Unlike wavelength multiplexed schemes, O-CDMA signals do not require bandwidth reservation and provides a fair division of bandwidth among all users. Users can be added to, or dropped from, the network with minimal reconfiguration of other users, allowing for soft capacity on demand and network flexibility. With tunable transmitters and/or receivers, format-independent transmissions may easily be configured to broadcast to all other users, multicast to selected users, or unicast to a single user. Network control can be decentralized, leading to increased network reliability and survivability. In all, the network control and management is simplified, a desirable quality in local access networks. O-CDMA additionally could provide data-independent physical layer security, since knowledge of the transmitter's codes is required to satisfactorily receive a signal [2], [3]. These motivations have been the driving force behind research in O-CDMA communications, and have produced various O-CDMA schemes, all presenting unique challenges [4].

Continual advancement in optical technology has resulted in increasingly sophisticated O-CDMA implementations. Recent testbeds have demonstrated the viability of several schemes, including time/wavelength encoding [5]–[7], spectral amplitude encoding of incoherent broadband sources [8], and spectral phase encoding [9]–[12]. Time/wavelength codes, which represent signals as a sequence of multiwavelength laser pulses, must allocate time slots within the bit time, sacrificing spectral efficiency. Spectral amplitude encoded O-CDMA systems use incoherent broadband sources, and thus the sensitivities of these systems are hampered at higher data rates (> 1 Gb/s) by excessive intensity noise generated by the source. Phase encoding schemes are susceptible to coherent beat noise occurring between the signal and multiaccess interference (MAI) of other users; however, using very long spreading codes [12] or synchronizing users' transmissions [9], [11] mitigates this problem.

We have been investigating a particular phase-coding scheme known as spectral phase encoded time spreading (SPECTS) [13], [14]. With this technique, a phase code is applied to the

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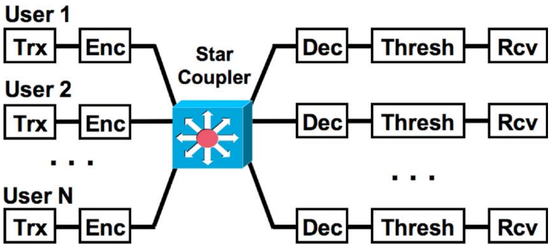

Fig. 1. Architecture of a typical O-CDMA system, composed of transmitters (Trx), encoders (Enc), decoders (Dec), thresholders (Thresh), and receivers (Rcv).

spectrum of a data-modulated femtosecond pulse, causing the pulse to spread out in time. The pulse can only be reconstructed (decoded) if an inverse or conjugate phase code is applied; otherwise, it remains spread out as MAI. The first comprehensive testbed using this technology demonstrated single-user transmission while applying pulse dispersion compensation and all-optical thresholding [15]. Our own initial SPECTS testbed was the first to investigate multiuser access for higher data rates (4 users at 1.25 Gb/s), where it showed that synchronous transmission was effective in minimizing the coherent beat interference between the signal and MAI [16]. Synchronous transmission has since been adopted into the testbed, despite the well-known simplicity that could be gained by allowing users to transmit asynchronously. Later adjustment to the testbed introduced time-multiplexed users as a way of exploiting the synchronous transmission and maximizing the throughput of the system [11]. Time multiplexing allows code sharing between different users, provided that they are not assigned to the same time slot. As an extension of code sharing, polarization multiplexing has been recently incorporated, allowing the testbed to perform with a bit-error-rate (BER) performance of BER $< 10^{-9}$ for up to 28 10-Gb/s users. Performance of this testbed was ultimately limited by coherent beat interference generated from accumulated MAI [17].

In this paper, we report on the most promising SPECTS O-CDMA testbed to date, a 10-Gb/s/user system with 32 error-free $(\text{BER} < 10^{-11})$ users. Unlike its earlier incarnations, this testbed does not show any apparent performance limitations (BER noise floor and per user power penalty) at the maximum number of users and also has 58% greater spectral efficiency. It incorporates forward error correction (FEC), and thus allows the recovery of errors caused by the coherent beat interference. Furthermore, the system employs a simple bandwidth suppression technique that minimally affects the BER performance while raising spectral efficiency. We first review the testbed and its major components (Section II), and then present the FEC-enhanced results, specifically comparing them to the previous non-FEC system [18] (Section III). Following this, we discuss the bandwidth suppression technique and its impact on the system performance, especially with regard to the spectral efficiency (Section IV).

II. SPECTS O-CDMA TESTBED DESCRIPTION

Our O-CDMA testbed follows the basic structure of a typical O-CDMA network, which is shown in Fig. 1. O-CDMA systems are generally configured in a star network, where each user has an encoder/decoder pair. A thresholder typically follows the decoder to detect the autocorrelation peak of the properly decoded signal and differentiate it from the MAI of incorrectly decoded signals. Our testbed, shown in Fig. 2, accommodates up to eight O-CDMA encoders coupled together into a single decoder, minimally allowing eight users. To further increase the effective number of users, a time multiplexer (time mux) and a polarization multiplexer (pol mux) have been added. With 9.95328-Gb/s (OC-192) data, the time mux produces a second data set offset ~50 ps from the original, while the polarization mux produces a separate orthogonally polarized data set. This ultimately allows up to 32 users (8 encoders × 2 time slots × 2 polarizations) to be supported on the system. We note that the system currently does not employ any transmission fiber, but transmission and recovery of femtosecond pulses (required for SPECTS) have been shown for up to 50 km of fiber [19], with actual SPECTS systems employing up to 2.5 km of fiber [15]. Work is currently being conducted on the testbed to include actual field fiber, and these will be reported at a later time. The following discusses the major components of the testbed.

A. Transmitter With FEC

The transmission of each user originates from a single source that consists of a mode-locked laser followed by a data modulator. The mode-locked laser produces 450-fs width pulses at a 9.95328-GHz repetition rate. The narrow temporal widths are necessary to create sufficient spectrum for SPECTS encoding and decoding. The pulse train is ON–OFF keyed via a $LiNbO_3$ Mach–Zehnder modulator with an OC-192 pseudorandom bit sequence (PRBS, length $2^{31} - 1$) that may be optionally FEC-encoded using a well-known Reed–Solomon code (RS(255, 239)). When FEC is in use, the data rate is lowered to 9.250698 Gb/s to accommodate the 6% coding overhead, maintaining OC-192 into the modulator. The modulated light pulses are distributed between the eight O-CDMA encoders and multiplexers. Although each user's data originates from the same source, delays on each mux and encoder path ensure that each users' data is offset by several bits. This decorrelates the PRBS between users and simulates individual data streams.

B. SPECTS Encoders and Decoder

The encoders and the decoder are composed of fiber pigtailed bulk-optics-based femtosecond pulse shapers, which are described in greater detail in [20]. Briefly, the encoded data streams are collimated onto diffraction gratings, spatially spreading out the spectral components of the incident pulses. The spread spectrum is incident upon a spatial light phase modulator (SLPM), which applies a phase shift to different portions of the spectrum, as designated by the O-CDMA codes. Additional phase shifts may also be applied to help compensate for dispersion in transmission fiber [15], [21]. To transfer the signal between the fiber components and bulk optic components, collimators are employed. In the testbed, significant savings in cost and space is achieved by employing

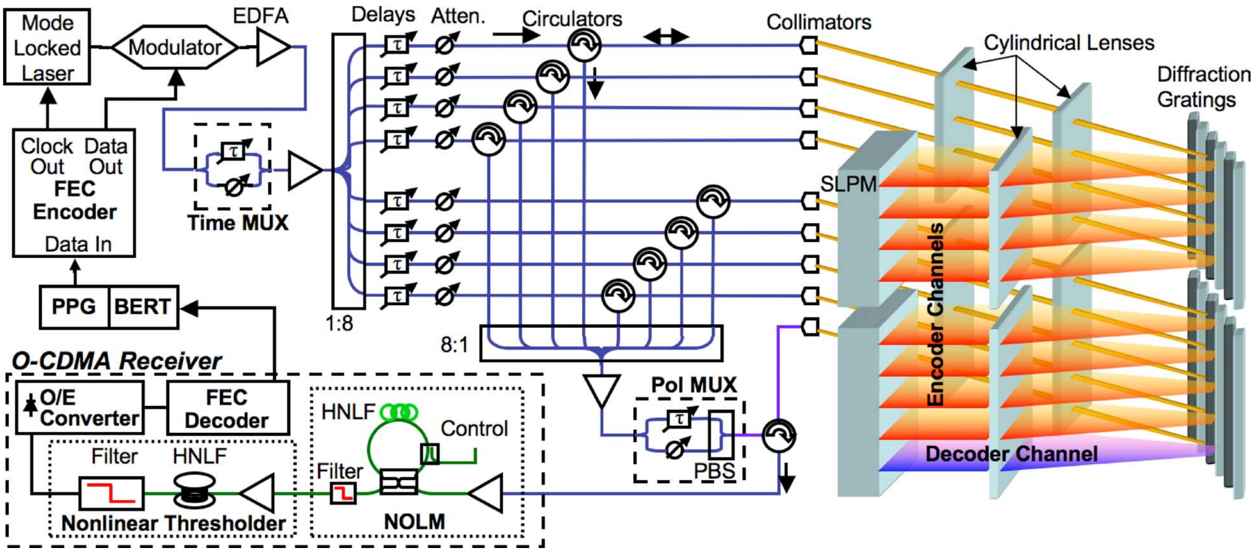

Fig. 2. Diagram of 32-user O-CDMA testbed with FEC. Experimental components include erbium-doped fiber amplifiers (EDFAs), attenuators (atten.), a pulse pattern generator (PPG), a bit-error-rate tester (BERT), and a polarization beam splitter (PBS).

TABLE I
64-CHIP WALSH CODES OF THE O-CDMA TESTBED

#	Code (1 = π phase shift, 0 = no phase shift)
5	1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0
6	1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1
16	1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1
28	1 0 1 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1
34	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1
40	1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1
52	1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
54	1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1

Code numbers have been designated by the *hadamard* command in MATLAB® and indicate the row or column of the generated symmetric matrix.

cylindrical optics and a reflective 2-D SLPM, as this allows multiple pulse shapers to be implemented in parallel using a single set of optics. Ultimately, the eight encoder channels and single decoder require only a pair of pulse shapers. After reflecting back into the fiber, circulators route the encoded signals through the remainder of the system. All O-CDMA-encoded data sets then combine to a single decoder that applies the conjugate phase code of the desired signal. Since both the circulator and the diffraction grating of the pulse shapers are polarizing, the decoder doubles as a polarization demultiplexer, selecting the desired polarization. Although the bulk optics of the current encoders/decoder prevent them from being used in a true telecom environment, the equivalent functions can be performed using compact and fiber-based arrayed waveguide gratings (which can spread and recombine the spectrum) and phase shifters [22], [23]. Such devices have been successfully employed in the testbed, but at lower spectral resolutions that those of the bulk optics pulse shapers [24]. More advanced devices are currently in development.

A key to achieving high performance in the O-CDMA system is the choice of codes. In this case, 64-chip Walsh codes are chosen since they ideally produce orthogonal signals when used synchronously. The MAI produced by Walsh codes never coincide with the correctly decoded signal, and are instead displaced to occur before or after it. This creates an interference-free window for the recovered pulse. In reality, slight irregularities in the pulse shapers cause the window to narrow, and we have thus chosen Walsh codes #5, 6, 16, 28, 34, 40, 52, and 54 for use in the encoders, since this particular subset produces an optimum window among all users (see Table I). For the measurements, Walsh code #5 is used in the decoder. Attempts to optimize the receiver for detecting the other codes are currently under investigation.

C. O-CDMA Receiver

The O-CDMA receiver performs postdecoder processing of the signal, and includes the thresholding function of Fig. 1. It also contains a nonlinear optical loop mirror (NOLM) which serves as a time gate for selecting between the two time multiplexed users. The NOLM switches through the desired time slot by impressing a π phase shift on the counterclockwise propagating signal, where the phase shift originates from cross-phase modulation induced within the nonlinear element, 500 m of highly nonlinear fiber (HNLF). The stimulus for cross phase modulation is a 3-ps, ~1540-nm control pulse stream with a

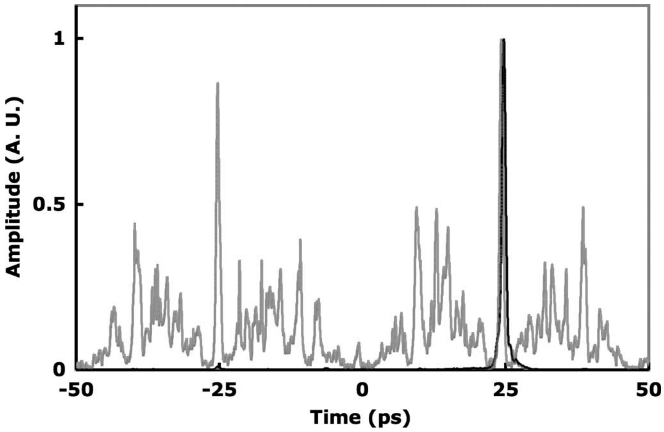

Fig. 3. Cross-correlations of the O-CDMA signal after decoding (gray) and after the NOLM time gate (black).

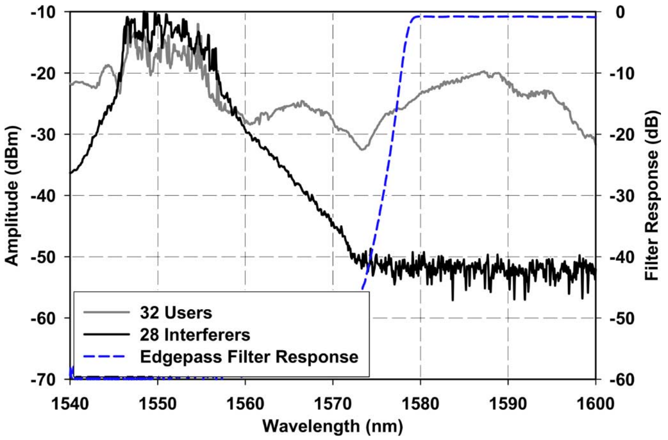

Fig. 4. Spectral response of the nonlinear thresholder.

repetition rate of 9.95328 GHz, aligned with the desired time slot. After the NOLM, the influence due to MAI is reduced by using a nonlinear thresholder, whose operating principle relies on spectral broadening resulting from self-phase modulation of incident signals within 500 m of HNLF. The correctly decoded signal will have high peak powers that can induce the spectral broadening, and these components may be filtered out and passed on to the optical/electrical (O/E) converter. MAI, with its relatively low peak power (despite having potentially high average power), will not generate spectral components within the filter's passband, and are thus suppressed. After gating and thresholding, the received signal is then FEC-decoded to produce the original data stream. The O-CDMA receiver response and BER results are given in the next section.

III. SPECTS O-CDMA TESTBED RESULTS WITH FEC ENHANCEMENT

A. O-CDMA Receiver Response

Before detecting and measuring the BER of the decoded signal, the O-CDMA receiver must apply time gating (through the NOLM) and thresholding. The decoded signal at the input of the O-CDMA receiver is shown in Fig. 3 as the gray trace. In this case, the system operates with all 32 users, but half have been deselected through polarization demultiplexing in the decoder. The remaining users distribute between two time slots in the range of -50 to 0 ps and 0 to 50 ps. Each time slot shares the same eight O-CDMA codes, so similar cross correlation traces appear in each slot. The slight differences between their intensity levels arise from coherent interference between the various O-CDMA users. The reconstructed correctly decoded signals clearly lie at ± 25 ps, and, as characteristic of the Walsh codes, they are surrounded by the MAI. The NOLM temporally gates the desired time slot, and the black trace of Fig. 3 shows the resulting output. The NOLM, with its 3-ps window, successfully passes the desired time slot while significantly suppressing the majority of MAI. The time gate is not ideal, however, in that MAI occurring within the 3-ps window still exits. Additionally, residue from the rejected time slot leaks through the NOLM and can be seen at -25 ps. To suppress this leakage and remaining MAI, the nonlinear thresholder is employed, and its spectral response is shown in Fig. 4. The output of the NOLM yields the gray spectrum after passing through the thresholder. Originally centered at 1550 nm, the spectrum broadens such that significant power is present at wavelengths longer than 1570 nm. These components may be filtered through to the receiver using an edgepass filter, which has a cutoff wavelength at 1578 nm (dotted line). In contrast, the black trace shows the thresholder response when only MAI is present in the system. In this case, the encoder containing code #5 is removed from the system, such that only 28 users remain. The decoder thus outputs only MAI from the remaining codes, and the thresholder input consists only of MAI that passes through the NOLM. The spectrum of the NOLM leakage is unable to generate self-phase modulation, and therefore, there is no spectral broadening. The thresholder is thus able to produce a contrast ratio of greater than 20 dB between the 32- and 28-user cases.

B. BER Performance Comparison Using FEC

After time gating and thresholding, the signal is sent into the O/E converter for BER measurements. Fig. 5 shows the results obtained with FEC in comparison to the testbed results reported in [17], which did not contain FEC. The independent axis indicates the received power per user incident upon the O-CDMA receiver, which contains the NOLM, optical thresholder, the O/E converter, and the optional FEC decoder. BER traces are obtained from 4 to 32 users, where an encoder is added to the system for each trace. Since each encoder contains two TDM time slots and two polarizations, four 10 Gb/s users are added to the system per encoder. For measurement without FEC [Fig. 5(a)], the FEC encoder and FEC decoder are removed from the system, and the testbed performs at $\text{BER} < 10^{-9}$ for up to 28 users. A noise floor builds with each added encoder, such that the 32-user case achieves only $\text{BER} < 10^{-8}$. The noise floor largely results from coherent beat interference that occurs between the signal and any coincident MAI, and it is present regardless of MAI thresholding. With the addition of FEC [Fig. 5(b)], the BER immediately improves such that all 32 users can remain error free for a period of at least 240 billion bits $(\text{BER} < 10^{-11})$. The arrows at the final points of each BER curve indicate the power at which this error-free point was

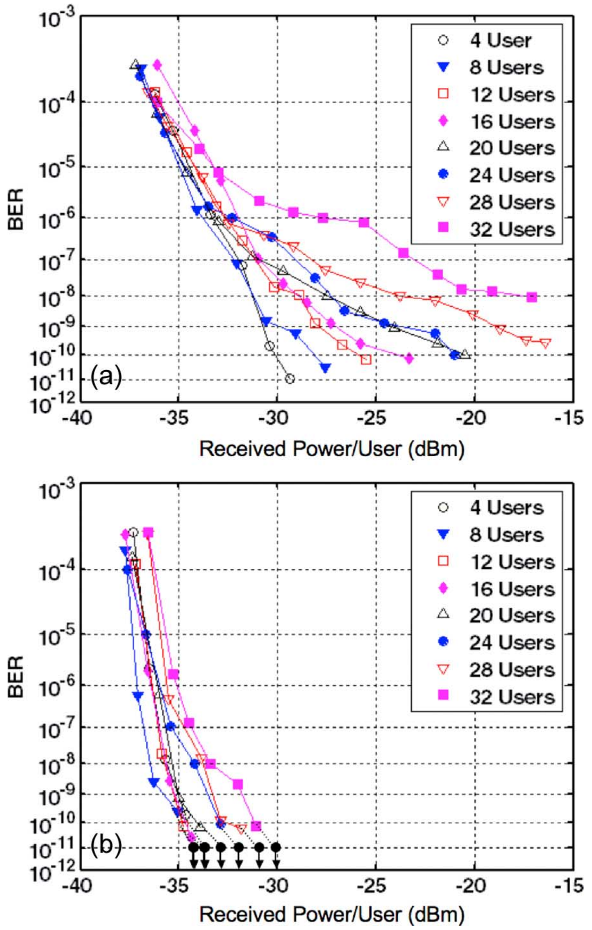

Fig. 5. BERs for the 32-user O-CDMA system (a) without and (b) with FEC. Fig. 5(a) results were presented in [17].

observed. Significantly, no error floor is evident for 32 users, suggesting that many more users could be added to the system before excessive coherent beat noise overcomes the FEC. For further comparison, Fig. 6 shows the power per user at $\mathrm{BER} = 10^{-9}$ as a function of users. Without FEC, the power per user clearly increases from -30.7 to -18.7 dBm going from 4 to 28 users, or a 22 dB penalty. With the FEC, sensitivity improves such that the power per user does not notably increase until going from 28 to 32 users (a 2.7-dB increase). Before this point, the power per user merely fluctuates between -36 dBm (8 users) to -33.4 dBm (28 users), a 2.6 dB range. The fluctuation, which is also evident without FEC, may be a manifestation of the wide BER variance that can be expected in a beat-noise limited coherent O-CDMA system [25].

IV. BANDWIDTH SUPPRESSION FOR INCREASED SPECTRAL EFFICIENCY

Following the BER improvement gained through FEC, we now attempt to increase spectral efficiency by reducing the system bandwidth. This section discusses the implementation of the narrowband system and then studies its subsequent performance. Since spectral efficiency is dependent on the system throughput, the narrowband system must maintain BER similar to the one obtained in the wideband system of Section III.

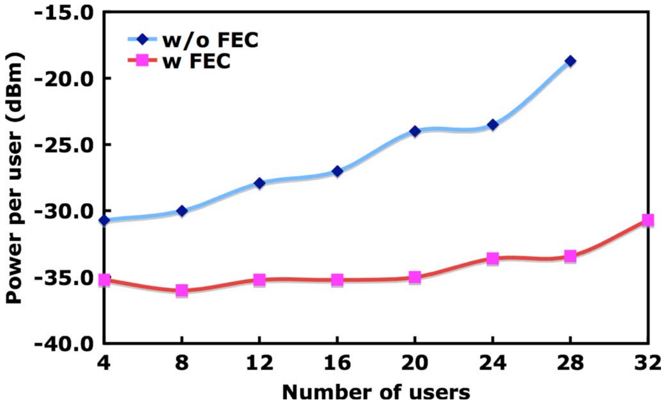

Fig. 6. Power per user versus the number of users for the O-CDMA system at $\mathrm{BER} = 10^{-9}$.

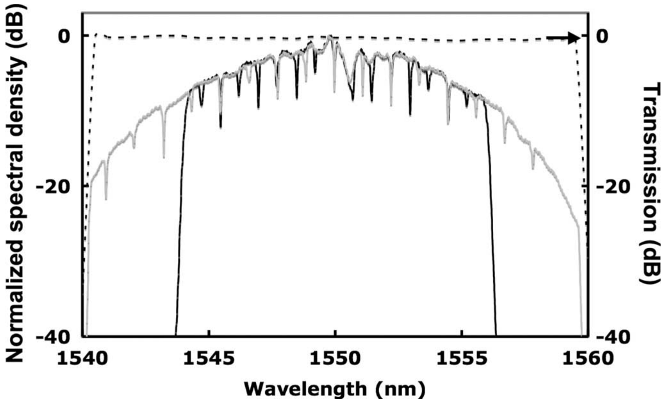

Fig. 7. Spectrum of encoded signal without (gray trace) and with bandwidth suppression (black trace). Transmission spectrum of the encoders/decoder is also shown (dotted line).

A. Narrowband Implementation

Bandwidth narrowing is easily performed on the testbed since O-CDMA encoders/decoder allow open access to the signal spectrum. Specifically, the spectrum spatially spreads out after refracting off the fiber Bragg gratings, and placing a physical aperture in its path effectively acts as a bandwidth filter. Fig. 7 demonstrates this implementation within the testbed. The gray trace shows the spectrum of an encoded signal from Section III with a 19-nm (2.4-THz) bandwidth, limited by the edges of the SLPM. Dips within the spectrum indicate the location of $0/\pi$ phase transitions within the O-CDMA code. To reduce the bandwidth, two beam blocks are placed within the path of the spread spectrum, effectively removing spectral components that are shorter than 1544 nm and longer than 1556 nm (black trace). The system bandwidth thus narrows to 12 nm (1.5 THz). To complete the bandwidth suppression, the SLPM is reprogrammed to apply the codes only over the narrowed region, and this is reflected by the changed location of the spectral dips. The effects of this bandwidth suppression are discussed below.

B. Impact of Bandwidth Suppression

Fig. 8 shows the autocorrelation traces of the correctly decoded pulse after the decoder both with and without the

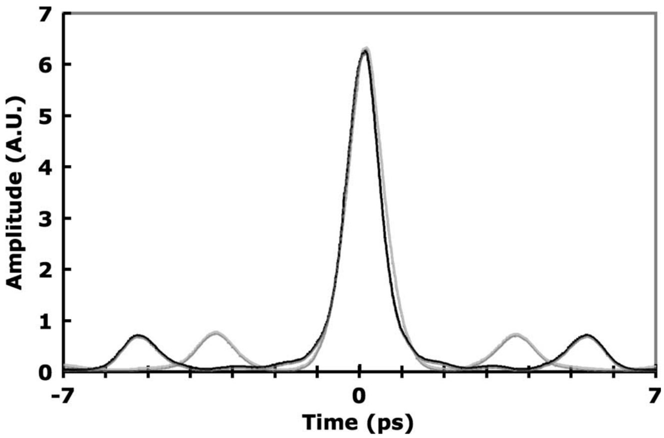

Fig. 8. Autocorrelation traces of the O-CDMA signal pulse without spectral narrowing (gray) and with spectral narrowing (black).

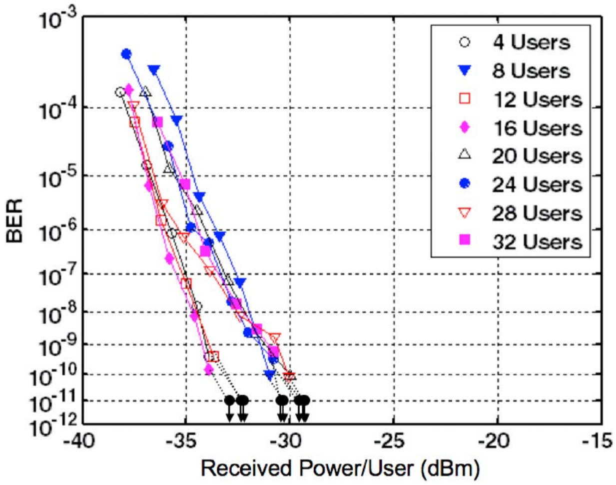

Fig. 9. FEC-corrected BERs for O-CDMA system with spectral narrowing.

bandwidth suppression. Even without bandwidth suppression, imperfect decoding, coupled with the initial transmission spectrum of the encoder/decoder (dotted line of Fig. 7), have caused the main peak of the pulse to spread beyond 450 fs, the initial width generated by the mode-locked laser. The presence of sidepeaks also results, but these are normally removed with the NOLM time gate. With bandwidth suppression, the sidepeaks shift from ±3.5 to ±5.3 ps away from the center peak, and is part of the expected temporal broadening. A slight pedestal also appears around the main peak, although the pulse width at full-width at half-maximum actually decreases from 883 to 816 fs, a 7.6% reduction. We would expect the main peak to eventually broaden with enough filtering, but for now the width does not change significantly enough to significantly affect peak power, the primary mechanism for the NOLM and the thresholder. Since these do not vary greatly, the performance of the NOLM and thresholder (and therefore BER) is minimally impacted. For verification, we observe the resulting FEC-corrected BER in Fig. 9. All users continue to perform at BER $< 10^{-11}$, with no obvious performance limit shown at 32 users. The sensitivity of the system likewise remains similar compared to Fig. 5(b), with power per user fluctuating between -34.2 dBm (16 users) and -30.4 dBm (eight users) at BER $= 10^{-9}$, a 3.8-dB range.

Given this performance, we evaluate the spectral efficiency of the testbed, defined as the system throughput divided by the system bandwidth. For the calculation, system throughput considers the amount of data transferred while maintaining BER $< 10^{-9}$ and the system bandwidth encompasses the total spectrum being encoded and decoded. The non-FEC system with full spectrum has a throughput of 278.7 Gb/s (28 users at BER $< 10^{-9}$) using 19 nm of bandwidth, and thus has 0.12 b/s/Hz spectral efficiency. Application of FEC alleviates the coherent beat noise limit and allows the system to support all 32 users. The system throughput increases, but FEC overhead impacts the throughput gain. Thus, the true data throughput is only 296 Gb/s, and the spectral efficiency remains the same at 0.12 b/s/Hz. Spectral efficiency improvement does not occur until the bandwidth reduction is applied. The narrowband implementation successfully maintains the 296-Gb/s throughput, but now only occupies 12-nm bandwidth. This results in a spectral efficiency of 0.20 b/s/Hz, or a 58% increase over the wideband systems.

V. CONCLUSION

As demonstrated, FEC can be a key technology in alleviating the performance limit imposed by coherent beat interference between the signal and MAI in SPECTS O-CDMA. With no apparent noise floor and minimal per user penalty, the testbed can clearly be expanded to support more users through the incorporation of additional O-CDMA encoders. Based on the BER performance of Fig. 5, Reed–Solomon coding would be effective so long as the noise floor of the non-FEC system remains below BER $= 10^{-6}$, and higher BERs could be tolerated using more powerful codes (e.g., turbo codes, LDPC, etc.). Simulations are currently being conducted to estimate the ultimate user limit for the testbed using the current FEC code.

The implementation of the testbed has thus far incorporated polarization and time multiplexing to increase the number of active users through code sharing. For further code sharing, it would be logical to incorporate wavelength multiplexing, where the system would contain multiple mode-locked lasers, each centered at different central wavelengths. The density of wavelength channels would be dependent on the total bandwidth of each laser, and therefore, spectral efficiency becomes an important figure to characterize the minimal possible spacing between their central wavelengths. We have demonstrated a simple method to narrow the bandwidth of the testbed and increase its spectral efficiency. It is well suited for implementing the wavelength division multiplexing (WDM)/O-CDMA hybrid as the hard filtering function assures minimal crosstalk between adjacent WDM/O-CDMA channels. In future investigations, we will determine the extent through which spectral narrowing can be applied without significantly broadening the pulse and affecting the performance of the O-CDMA receiver.

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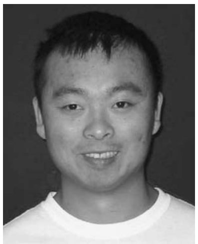

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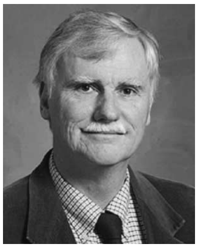

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