LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-CONF-210103

Demonstration of Record BER and Number of Users for Optical CDMA (O-CDMA), with Implications to Secure Communications

A. J. Mendez, V. J. Hernandez, C. V. Bennett, R. M. Gagliardi, W. J. Lennon

March 1, 2005

Optical Fiber Communications
Anaheim, CA, United States
March 6, 2005 through March 11, 2005

Disclaimer

Demonstration of Record BER and Number of Users for Optical CDMA (O-CDMA), with Implications to Secure Communications

A. J. Mendez[a] , V. J. Hernandez*[b] , C. V. Bennett*, R. M. Gagliardi[c], and W. J. Lennon*

[a]*Mendez R&D Associates, P.O. Box 2756, El Segundo, CA 90245, Phone: (310) 640-0497, MendezRDA@AOL.com*
**Lawrence Livermore National Laboratory (LLNL), P.O. Box 808, L-229, Livermore, CA 94551;*
[b]*University of California at Davis, Department of ECE, Davis, CA 95616*
[c]*Department of EE-Systems, University of Southern California, Los Angeles, CA 90089-2565*

Abstract: We demonstrate a BER of 10^{-11} for 16 simultaneous users, using wavelength/time O-CDMA. We show the extent to which severe multi-access interference can be used to mask and/or degrade the signal from an intruder.

1.0 Introduction

We've been developing an O-CDMA technology demonstrator (TD) based on wavelength/time (W/T) matrix codes [1],[2]. The code construction produces more codes (32) than constituent wavelengths (8), so the coding acts as a wavelength multiplier. In this paper we describe the TD and experimental set-up by which we demonstrated a record combination of number of simultaneous users (16), per user data rate (1.25 Gb/s), BER (10^{-11}), and high spectral efficiency (8x8 matrix codes). Previous work described eight users at BER > 10^{-9} [3] and 16 users at BER >10^{-2} [4].

At a large number of users, as in our experiment, the multi-access interference (MAI) is severe because the TD is based on optical orthogonal codes (OOCs) and intensity modulation/direct detection (IM/DD) and, thus, there are no cancelling terms. We therefore perform two additional experiments to investigate the possibility of using the severe MAI to mask or detect a signal. The first intercepts the shared fiber ahead of the correlator, to see if the encoded signal could be detected and deciphered by an intruder, and the second intercepts the signal after the decoder, but with only interferers active, to see if "leakage" due to MAI can be used to decipher "fellow" signals.

2.0 The O-CDMA TD and Measurement Results

The table shows the three kinds of experiments performed. Row one represents the usual test configuration for determining the performance aspects of an O-CDMA system. The second and third rows represent the exploration configurations to see whether O-CDMA is vulnerable to intrusion and whether severe MAI can be used to mask an encoded signal if the bit-error-rate (BER) performance is very good and number of users (hence MAI) very large.

Test Configuration	Simultaneous Users	Measurements
Matched encoder/decoder plus interferers	1…16	Eye-diagram and BER
Tap ahead of the decoder and detect 1 wavelength	1…16	Eye-diagram and BER
Unmatched encoder/decoder (interferers only)	1…4	Eye-diagram and BER

The TD (see Fig. 1) is the platform for these experiments. A single source, called the encodable carrier (EC), provides multiple wavelength pulses to multiple encoders. It is generated by externally modulating an eight-wavelength continuous wave (cw) source with 100 ps pulses at a repetition rate of 1.25 GHz. A second modulator on-off keys the pulse stream, adding a 2^{31}-1 length pseudo random bit sequence (PRBS). The multiwavelength pulse stream is distributed to 16 encoders, whose details are shown in the inset on the left side of Fig. 1. Each encoder consists of an arrayed waveguide grating (AWG) that wavelength demultiplexes the pulse stream and a series of delays lines that place the pulses in their appropriate time chips. Couplers then combine four of the displaced pulses to form an encoded signal. Rather than discarding the remaining four pulses, a feature of the W/T matrix codes allow these pulses to form another code, and thus each encoder can produce two encoded (and orthogonal) signals. In all, eight encoders generate sixteen encoded signals. The encoded signals combine through a network of couplers into a single decoder. To simulate sixteen different users, the sixteen path lengths to the decoder are sufficiently different to decorrelate the PRBS contained between paths. The decoder is tuned to Code 9 of the code set and has the same structure as the encoder of Code 9, but with inverse delays. The decoded signal proceeds to the receiver module, which consists of a 10 GHz receiver followed by a 10 GHz D Flip-Flop (DFF). The DFF is clocked at 1.25 GHz, the same as the signal's data rate. A phase shifter adjusts the clock such that its rising edge coincides with the optimum eye opening of the decoded signal, gating out any non-coincident MAI and producing a clean non-return-

UCRL-CONF-210103

to-zero (NRZ) 1.25 Gb/s signal.

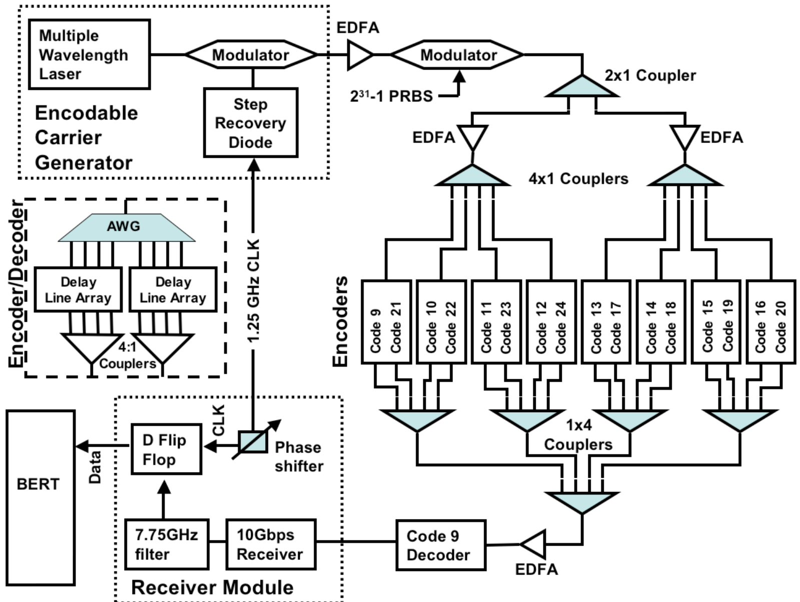

Fig. 1: Set-up for the sixteen user technology demonstrator.

Fig. 2 shows eye diagrams of incoming decoded signals along with BER of the recovered data stream. The back-to-back case bypasses the encoders and decoder while the one user case disconnects all encoder outputs, except the output of encoder 9. Neglible penalty occurs between the two cases. Subsequent users are added by reconnecting the encoder outputs in numerical order, and thus a second user adds Code 10, a third user adds Code 11, etc. As seen in the eye diagrams, each added user adds a MAI peak to the decoder ouput, which surround the desired signal. To keep the desired signal open at a high number of users, coarse delays (~100 ps) were applied to seven interferers that would otherwise totally overlap the desired signal. The delays must be applied to avoid coherence effects that result from sharing the single source. (This effect would be significantly reduced if each encoder had its own encodable carrier generator.) For the BER curves, power penalties occur as a result of the added power of the MAI contributed by addional users. At a larger number of users (12 to 16 users), a noise floor becomes apparent. This floor results from the tails of MAI peaks that are adjacent to the desired signal. These tails leak into the sampling window and at a high number of users accumulate enough to cause noticable coherent interference with the desired signal. Regardless, BER of at least BER < 10^{-11} can be achieved for all 16 users. The arrow at the end of the BER curves indicate the minimum power into the receiver module at which no errors occurred for the course of 100 billion bits.

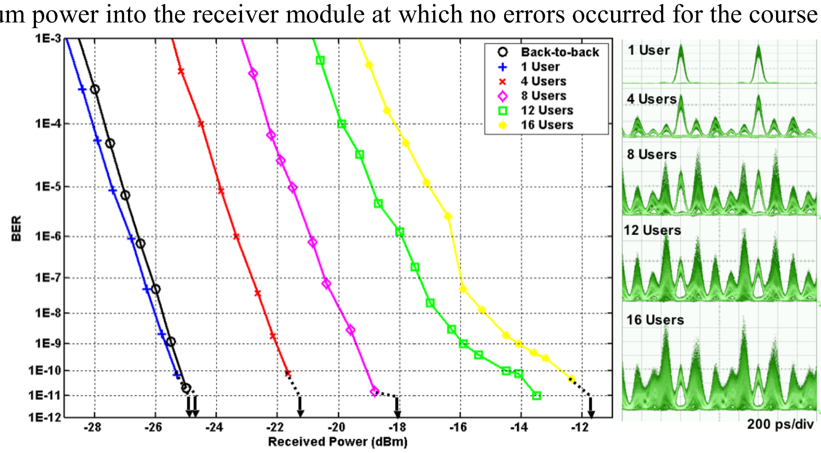

Fig. 2: BER measurements and eye diagrams obtained from the O-CDMA technology demonstrator for one to sixteen users.

Fig. 3a shows the BER and eye-diagrams in a scenario where an intruder, assuming WDM transmission, taps off a single wavelength of the encoded signal before the decoder and attempts to detect or deceipher the signal without actually decoding the signal. The intruder is assumed to have the same receiver structure as shown in Fig. 1.

For all number of users (one to sixteen), a signal is indeed detectable with nontrivial BER. This lends support to the need for true frequency hopping or rolling codes to avoid this means of intrusion. Fig. 3b shows the bit-error-rates after the decoder, but with the desired signal (Code 9) turned off. In this scenario, a signal can be derived from the MAI of other users unless the users exceed four. At this point, the MAI of the fourth user falls directly on top of the intercepted signal leading to a significant floor that does not exceed BER<10^{-2}.

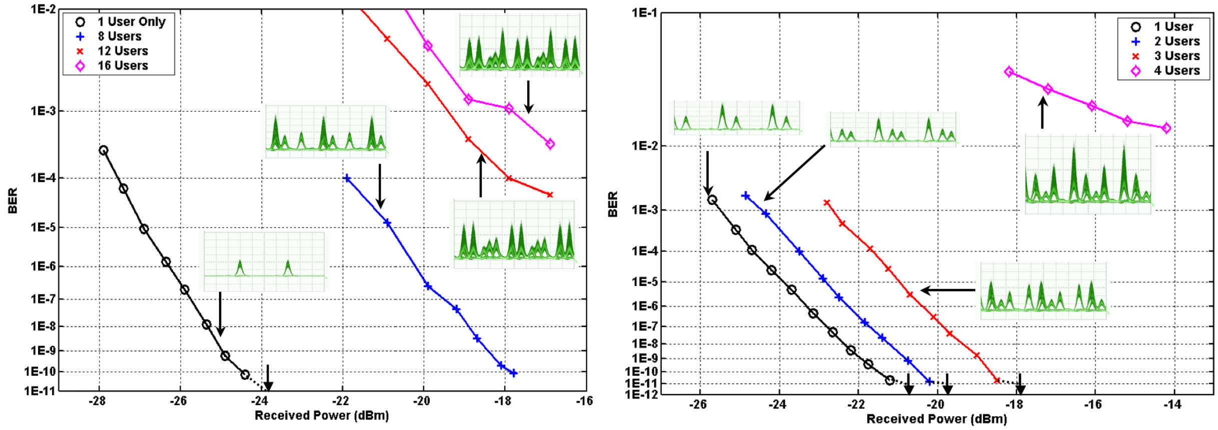

Fig. 3: BER and eye diagram measurements for (a) ahead of the decoder and (b) intrusion after the decoder.

3.0 Summary and Conclusions

O-CDMA has been proposed for communications with increased physical security based on a (1) massive code space of frequency hopping/time spreading codes [5] and (2) concepts from quantum cryptography, but using coherence multiplexing [6]. Still, there has been a nagging concern in the community that O-CDMA may not offer that much physical security. We posit that O-CDMA can be made to resemble chaotic masking (CMS) optical communications [7],[8], provided the MAI is severe. The MAI can be made to be severe if the system concept is based on OOCs and IM/DD, if the system concept supports many concurrent users (>16), and if the desired signal can be received with extremely good BER performance in the presence of the severe MAI. But beyond the chaotic aspect, O-CDMA for secure communications can benefit from frequency hopping and rolling codes.

Finally, although we've achieved a record number of users and BER, we still have not exhausted all of the W/T code set, nor have we used techniques such as optical hard-limiting. Thus, in the future we expect to increase the number of simultaneous users beyond sixteen and, therefore, increase the chaotic nature of O-CDMA communications.

Acknowledgments: This effort was supported in part by U.S. Department of Energy SBIR Phase II Grant ER83277 and performed under the auspices of the U.S. Department of Energy by the University of California LLNL under contract No. W-7405-Eng-48 and a subcontract to ER83277. The collaboration between MRDA and LLNL was carried out under Cooperative Research and Development Agreement TC-2051-02.

References

[1] Mendez, A. J., Gagliardi, R. M., Hernandez, V. J., Bennett, C. V., Lennon, W. J. (2004). High Performance Optical CDMA System Based on 2D Optical Orthogonal Codes. *J. Lightwave Technol.* 22(11):2409 – 2419.

[2] Hernandez, V. J., Mendez, A. J., Bennett, C. V., Lennon, W. J. (2004). Bit-Error-Rate Performance of a Gigabit Ethernet O-CDMA Technology Demonstrator (TD). Conf. Proc., 2004 IEEE/LEOS. Paper WE5:499-500.

[3] Kissing, J., Voges, E. Pfeiffer, T. (2001). A robust and flexible all optical CDMA multichannel transmission system for the access domain. In: Optical Fiber Communication Conference and Exhibit, 2001. Paper TuV2.

[4] Wei, D., Ayotte, S., Mathlouthi, W., LaRochelle, S., Rusch, L. (2003). BER performance of an optical fast frequency-hopping CDMA system with multiple simultaneous users. Conf. Proc. OFC 2003, Paper ThQ1:544-546.

[5] L. Tancevski, I. Andonovic, and J. Budin. (1995). Secure optical network architectures utilizing hybrid wavelength hopping/time spreading codes. *IEEE Photonics Technol. Lett.* 7(5): 573-575.

[6] Wells, W., Menders, J., Miles, E., Loginov, B., Hodara, H. (2002). Another Alternative to Quantum Cryptography. *Quantum Information Processing* 1(1 / 2):91-106.

[7] Mirasso, C. R. (2005). Chaotic Optical Communications. *IEEE LEOS Newsletter*. 19(1):12-14.

[8] Kanakidis, D., Argyris, A., Syvridis, D. (2003). Performance Characterization of High Bit-Rate Optical Chaotic Communication Systems in Back-to-Back Configuration. *J. Lightwave Technol.* 21(3):750 – 758.