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Bit-Error-Rate Analysis of a 16-User Gigabit Ethernet Optical-CDMA (O-CDMA) Technology Demonstrator Using Wavelength/Time Codes

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***Abstract*—This letter describes a technology demonstrator for an incoherent optical code-division multiple-access scheme based on wavelength/time codes. The system supports 16 users operating at 1.25 Gsymbols/s/user while maintaining bit-error rate (BER) $< 10^{-11}$ for the correctly decoded signal. Experiments support previous simulations which show that coherent beat noise, occurring between the signal and multiple access interference, ultimately limits system performance.**

***Index Terms*—Access codes, code-division multiaccess, codes, encoding, multiaccess communication, optical fiber communication.**

I. INTRODUCTION

OPTICAL code-division multiple-access (O-CDMA) is an attractive technology since it potentially provides flexible, robust, and asynchronous communications in access networks. O-CDMA schemes are categorized as implementing the code through the optical field and relying on coherent detection, or through time slots and wavelengths with reliance on incoherent detection. Coherent schemes are susceptible to coherent beat noise that occurs when the correctly decoded signal temporally overlaps with the multiple access interference (MAI) from other users [1]. Thus, recent implementations of coherent O-CDMA resort to timing coordination between users, ranging from complete bit-level synchronization [2] to time slot assignment within the bit [3]. Another approach uses very long spreading codes to minimize the amplitude of the MAI while keeping users asynchronous; however, only ten of 512 possible codes deliver adequate bit-error-rate (BER) performance ($\text{BER} < 10^{-9}$) [4]. Incoherent schemes are less susceptible to coherent interference [5], but due to time slot allocation, are difficult to implement and less spectrally efficient with increasing data rates and time slots.

We have been investigating a wavelength/time O-CDMA system utilizing codes derived from folded Golomb rulers, which have the advantage over other codes in requiring fewer time slots [6]. Simulations show that a 32-user code-weight-four system may be implemented with only eight wavelengths and eight time slots, if optical hard limiting (OHL) is used [7]. Without OHL, at least 16 users are possible. Because of these results, a technology demonstrator (TD) operating at Gigabit Ethernet rate (1.25 Gsymbols/s/user) has been constructed to implement the codes in a robust, low-cost, and simple manner; [7] gives an initial description of the TD, but it does not include BER performance. O-CDMA systems based on other coding methods have reported performance of $\text{BER} < 10^{-9}$, but these systems contain a low number of users (four or less) [8], [9]. This letter reports BER performance of the TD for 16 users, exceeding the user count of these other systems. Coherent beat noise in this system is less compared to coherent O-CDMA schemes, but it still impacts system performance. We applied delays to avoid overlap between the signal and the MAI reduce the beat noise, allowing the decoded user to achieve excellent performance ($\text{BER} < 10^{-11}$) when all other users are present in the system. Further measurements investigate the amount of overlap that can be tolerated to achieve adequate BER performance.

II. TECHNOLOGY DEMONSTRATOR SETUP

Fig. 1 shows the layout of the TD. A single source, called the encodable carrier (EC), provides multiwavelength return-to-zero (RZ) pulses to 16 encoders. It is generated by externally modulating an eight-wavelength continuous-wave source with 100-ps pulses at a repetition rate of 1.25 GHz. The wavelengths range from 1543.73 to 1549.32 nm, with 100-GHz spacing. The electronic pulses originate from a step recovery diode driven by a 1.25-GHz clock. The EC is ON–OFF-keyed with a $2^{31}-1$ length pseudorandom bit sequence (PRBS) using a Mach–Zehnder LiNbO_3 modulator and distributed to the 16 encoders. Each encoder has a different path length to decorrelate the PRBS pattern between users. Additionally, the delays remove the synchronism between bits of each encoder. The inset of Fig. 1 shows the detail of each encoder. Each contains

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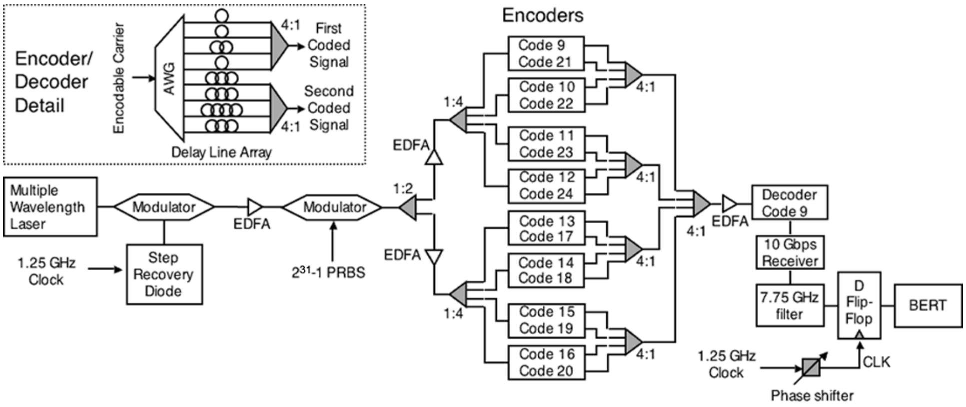

Fig. 1. Setup for the O-CDMA TD with details of the encoder and decoder shown in the inset.

an arrayed waveguide grating that wavelength demultiplexes the EC into eight synchronous pulse streams. A series of delay lines in the encoder place the pulses in their appropriate time slots, and couplers combine four of the displaced pulses to form an encoded signal. The remaining four pulses form a second, orthogonal, encoded signal. Thus, the eight encoders of the system generate 16 encoded signals, using Codes 9 through 24 of the code set specified in [7]. The decoder, tuned to Code 9, has the same structure as the corresponding encoder, but with inverse delays to realign the pulses. To reshape the decoded signal into nonreturn-to-zero (NRZ)-type format (making it more compatible with clock recovery circuitry and traditional digital electronics), the 10-GHz receiver contains a limiting amplifier and a threshold control that levels the "1" and "0" levels of the decoded signal, followed by a 13-Gb/s D flip-flop (DFF) that acts as a time gate. The DFF is clocked at 1.25 GHz, the same as the system data rate. A phase shifter adjusts the clock so that its rising edge coincides with the optimum eye opening of the decoded signal, gating out any noncoincident MAI and producing a clean NRZ 1.25-Gb/s signal. The analog bandwidth of the DFF provides a gating window of ∼25 ps.

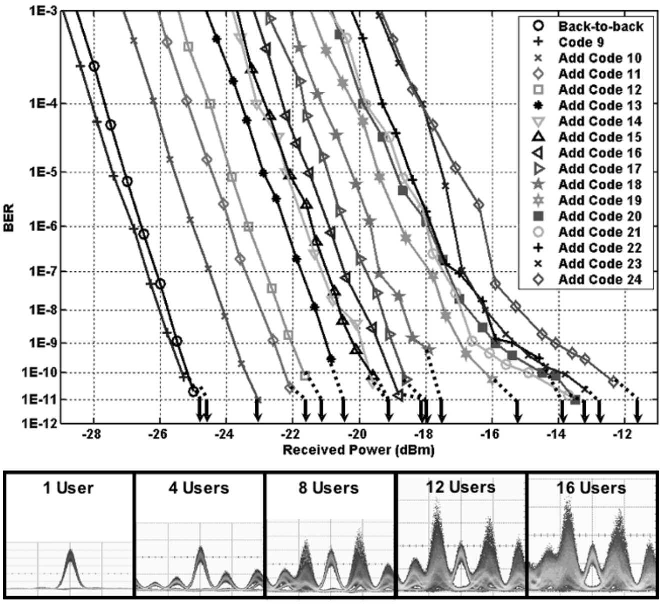

Fig. 2. BER and eye diagrams of the TD. Eye diagram scaling: 100 ps/div with normalized amplitude.

III. RESULTS AND DISCUSSION

Fig. 2 shows BERs and eye diagrams obtained from the TD, where eye diagrams were captured with a separate 30-GHz photodetector. The horizontal axis of the BER graph indicates the average optical power incident upon the 10-GHz receiver, and the arrows indicate the power at which no errors occur over a period of 300 billion bits, for a performance of BER $< 10^{-11}$. In the one user case, only Code 9 transmits, and the decoder autocorrelation reproduces a single pulse consisting of four wavelengths of equal weight. Its BER performance shows negligible penalty from the back-to-back case, where all encoders and the decoder have been removed. With the addition of more users, MAI peaks begin to appear around the decoded signal, with codes added sequentially from Codes 10 to 24. Since the MAI is quantized to the coding weight of a single wavelength, each MAI peak is approximately one quarter the amplitude of the decoded signal. These MAI peaks directly add to the power incident upon the receiver, without necessarily degrading the quality of the decoded signal. The true BER power penalty, i.e., the amount of increased *decoded signal power* required to maintain a given BER, can be obtained by subtracting the weight of other users' codes from the total power increase measured at the receiver. Table I summarizes the ideal weights versus measured power increases associated with each additional user, and their difference determines the penalty required to achieve BER $= 10^{-9}$ when compared to the single-user case. Ideally, the measured power increase from each added user equals the total weight of wavelengths shared with Code 9, and although not implemented in the TD, this weight may be physically removed using optical time gating [10]. Code 10 shares two wavelengths with Code 9, thus, it raises the cumulative weight at the decoder from four to six, or 1.76 dB. The true penalty is given by any power increase in excess of the coding weight. For less than 11 users, the penalty mostly falls below 0.5 dB and may be attributed to nonuniform losses contained within encoder components and the path to the decoder. The penalty exceeds 1 dB at 11 users and greater, as a noise floor becomes apparent for these measurements. The cause of the floor becomes evident by comparing the 8- and 12-user eye diagrams of Fig. 2. At 12 users,

TABLE I
SUMMARY OF USER WEIGHTS AND POWER PENALTIES FOR TECHNOLOGY DEMONSTRATOR, K = Number of Users

K	Code Added	Cumulative Weight	Cumulative Weight (dB)	Measured Power Increase (dB)	True Penalty (dB)
1	9	4	--	--	--
2	10	6	1.76	1.94	0.18
3	11	7	2.43	3.04	0.61
4	12	9	3.52	3.62	0.10
5	13	11	4.39	4.7	0.31
6	14	13	5.12	5.51	0.39
7	15	14	5.44	5.54	0.10
8	16	16	6.02	6.16	0.14
9	17	18	6.53	6.68	0.15
10	18	20	6.99	7.4	0.41
11	19	23	7.60	8.79	1.19
12	20	25	7.96	9.7	1.74
13	21	25	7.96	9	1.04
14	22	27	8.29	9.99	1.70
15	23	30	8.75	10	1.25
16	24	32	9.03	11.7	2.67

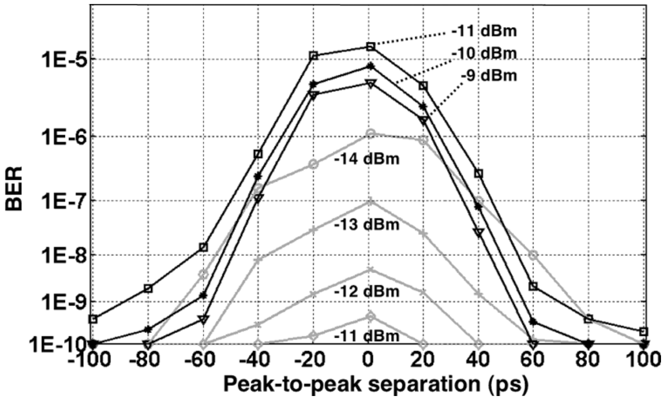

Fig. 3. BER of the correctly decoded signal as a function of peak-to-peak separation between a single multiaccess interferer (grey) and a second interferer (black).

the tails of the MAI peaks begin spilling into the sides of the decoded signal. This closes the eye and causes beat noise, degrading the BER.

The coherent beat noise is inherent in the TD because all encoders share the single EC; it will be mitigated if each user has its own source. The beat noise can be minimized by applying delays to the seven worst-case interfering users. An investigation of this is given in Fig. 3, which gives the BER of the decoded signal as a function of separation between MAI and signal peaks. The grey curves show the case for a single MAI peak scanning through the decoded signal. The measurement is taken for four different receiver-incident powers covering a 3-dB range of -14.0 to -11.0 dBm. At -14.0 dBm, there is a ~140-ps range over which the signal has BER $> 10^{-9}$ peaking at 1.1×10^{-6} when the MAI completely coincides with the signal. If BER $= 10^{-9}$ is the minimum acceptable BER performance, the decoded signal can tolerate an MAI peak occurring in 77.8% of the total bit period (800 ps). The percentage increases with increasing power, reaching 100% at -11.0 dBm. If an MAI peak is coincident with the signal and a second MAI peak is scanned, the results are as shown on the black curves. When the two MAI peaks coincide with the signal, the BER degrades from 4.6×10^{-11} in the single MAI case to 1.4×10^{-5} at -11 dBm. The improvement obtained by increasing overall power into the receiver is greatly reduced, with the BER improving to only 5.2×10^{-6} when 2 dB is added. These results agree with recent simulation results indicating that the performance of an asynchronous system will encounter a BER floor as the number of users increase [8].

IV. CONCLUSION

We have presented a 16-user O-CDMA TD that achieves BER $< 10^{-11}$ while operating at 1.25 Gsymbols/s/user. The true power penalty incurred from additional users is minimal until the onset of coherent beat noise. Beat noise may be reduced by providing sufficient distance between MAI and the desired user, as well as increasing overall power into the receiver for a single MAI peak. Although previous simulations show the TD is limited to 16 users without OHL, these do not consider time gating to mitigate MAI [10], and time gating has been included in the TD by using a DFF. Future work will increase the number of users and reduce the delay dependence. The ultimate goal is achieving a truly asynchronous TD supporting the full cardinality of the code set.

REFERENCES

[1] V. J. Hernandez, D. Yixue, C. Wei, R. P. Scott, K. Li, J. P. Heritage, D. Zhi, B. H. Kolner, and S. J. B. Yoo, "Spectral phase-encoded time-spreading (SPECTS) optical code-division multiple access for terabit optical access networks," *J. Lightw. Technol.*, vol. 22, no. 11, pp. 2671–2679, Nov. 2004.

[2] R. P. Scott, C. Wei, K. Li, V. J. Hernandez, B. H. Kolner, J. P. Heritage, and S. J. B. Yoo, "Demonstration of an error-free $4 * 10$ Gb/s multiuser SPECTS O-CDMA network testbed," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2186–2188, Sep. 2004.

[3] J. Zhi, S. Dongsun, Y. Shangda, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, "Four-user 10-Gb/s spectrally phase-coded O-CDMA system operating at ~30 fJ/bit," *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 705–707, May 2005.

[4] W. Xu, N. Wada, T. Hamanaka, K. Kitayama, and A. Nishiki, "10-user, truly-asynchronous OCDMA experiment with 511-chip SSFBG en/decoder and SC-based optical thresholder," presented at the *Optical Fiber Commun. Conf. (OFC)*, Anaheim, CA, Mar. 6–11, 2005, Paper PDP33.

[5] W. Xu and K. Kitayama, "Analysis of beat noise in coherent and incoherent time-spreading OCDMA," *J. Lightw. Technol.*, vol. 22, no. 10, pp. 2226–2235, Oct. 2004.

[6] A. J. Mendez, R. M. Gagliardi, V. J. Hernandez, C. V. Bennett, and W. J. Lennon, "Design and performance analysis of wavelength/time (W/T) matrix codes for optical CDMA," *J. Lightw. Technol.*, vol. 21, no. 11, pp. 2524–2533, Nov. 2003.

[7] ——, "High-performance optical CDMA system based on 2-D optical orthogonal codes," *J. Lightw. Technol.*, vol. 22, no. 11, pp. 2409–2419, Nov. 2004.

[8] V. Baby, I. Glesk, R. J. Runser, R. Fischer, H. Yue-Kai, C. S. Bres, W. C. Kwong, T. H. Curtis, and P. R. Prucnal, "Experimental demonstration and scalability analysis of a four-node 102-Gchip/s fast frequency-hopping time-spreading optical CDMA network," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 253–255, Jan. 2005.

[9] J. Faucher, R. Adams, L. R. Chen, and D. V. Plant, "Multiuser OCDMA system demonstrator with full CDR using a novel OCDMA receiver," *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 1115–1117, May 2005.

[10] I. Glesk, V. Baby, C. S. Bres, X. Lei, D. Rand, and P. R. Prucnal, "Experimental demonstration of a 2.5 Gbps incoherent 2-D OCDMA system," presented at the Conf. Lasers and Electro-Optics (CLEO). IEEE, vol. 1, 2004, Paper CWH1, p. 2.