Spectrally Efficient Optical CDMA Using Coherent Phase-Frequency Coding

Shahab Etemad, *Member, IEEE*, Paul Toliver, Ron Menendez, Jeff Young, Tom Banwell, Stefano Galli, Janet Jackel, *Senior Member, IEEE*, Peter Delfyett, *Fellow, IEEE*, Craig Price, and Terry Turpin, *Member, IEEE*

***Abstract*—We demonstrate feasibility of a spectrally efficient wavelength-division-multiplexing-compatible optical code-division multiple-access system using 16 phase-locked laser lines within an 80-GHz tunable window as frequency bins and an ultra-high frequency resolution spectral phase encoder–decoder. Coding and decoding using binary [0, π] phase chips were demonstrated for four users at 2.5 Gb/s, and a single coded signal was separated from four copropagating signals, with bit-error rate $< 10^{-9}$.**

***Index Terms*—Code-division multiple-access (CDMA), code-division multiplexing, optical code-division multiple-access (OCDMA), optical communications, wavelength-division multiplexing (WDM).**

I. INTRODUCTION

THE SUCCESS and widespread use of code-division multiple-access (CDMA) in the wireless domain has renewed interest in exploring its use in the optical domain, which, however, presents a very different set of challenges [1]. These include spectral efficiency, which is typically low in optical CDMA (OCDMA), intersymbol interference, and susceptibility to network impairments. Here we describe the conceptual basis and initial results for a novel phase-frequency approach to OCDMA that is compatible with existing transparent reconfigurable optical networks, has high spectral efficiency, and is minimally affected by transmission impairments. Initial experimental results demonstrate 12.5% spectral efficiency and simulations demonstrate that greater than 50% spectral efficiency can be achieved by straightforward extension of current work.

Coding and decoding are based on modifying the relative spectral phases of the set of well-defined phase-locked frequencies that are the output of a mode-locked laser (MLL). We use 16 equally spaced phase-locked laser lines confined to an 80-GHz window. We view this window as comprising 16 frequency bins and phase encode each bin using a coder based on a novel ultra-high resolution optical demultiplexer. Compared with previous conceptually similar work that had used the very broad optical bandwidth of an ultrashort pulse source [2], our approach has the advantage of coding discrete frequency lines and can use a small and tunable window which is compatible with ordinary wavelength-division multiplexing (WDM) [3]. The narrower spectral extent of the coded signal also limits the effects of transmission impairments such as dispersion.

II. CODING CONCEPTS

The encoding process begins with a train of short pulses, with spectral content comprising a stable comb of closely spaced phase-locked frequencies; these are generated by an MLL and have a frequency spacing equal to the MLL pulse repetition rate. This source, which can be limited to an 80-GHz total spectral width using an optical bandpass filter, can be positioned spectrally within any desired WDM window by tuning the optical filter. The phase-locked addition of these frequencies generates a pulse train with a pulsewidth of 12.5 ps, inversely proportional to the spectral width of the window. These pulses can subsequently be modulated to carry data.

Encoding consists of separating each of these frequency bins, shifting its phase, in this case by 0 or π, as prescribed by the choice of code, and recombining the frequency bins to produce the coded signal. When the relative phases of the frequencies are shifted, the set of frequencies is unaltered, but their recombination results in a different temporal pattern: e.g., a pulse shifted to a different part of the bit period, multiple pulses within the bit period, or noise-like distribution of optical power. Each OCDMA code is defined by a unique choice of phase shifts. The challenge is to define a set of codes that make efficient use of the spectrum within the window, and that can also be separated from each other with acceptable error rates, even when a maximum number of codes occupy the window.

For initial implementation we have chosen the set of Hadamard codes, which are orthogonal and binary. This choice is based on the goal of high spectral efficiency with minimal multiuser interference (MUI). Unlike many optical coding schemes that have been proposed, ours offers true orthogonally in the sense that MUI is zero at the time that the decoded signal is maximum. The number of orthogonal codes is equal to the number frequency bins; hence, high spectral efficiency is possible.

Binary Hadamard codes are converted to phase codes by assigning to $+1$s and -1s phase shifts of 0 and π, respectively. To encode data, which contains a spread of frequencies, as opposed to the unmodulated pulse stream, which contains only the initial comb of frequencies produced by the MLL, it is necessary to define frequency bins around the center frequencies. Encoding data then consists of applying the phase shift associated with a frequency to the entire bin. The output of the phase encoder is

---

Manuscript received August 27, 2004; revised October 15, 2004. This work was supported in part by Defense Advanced Research Projects Agency (DARPA) MTO under Contract MDA972-03-C-0078 and NIST ATP. Any opinions, findings and conclusions or recommendations expressed in this material are solely those of the author(s).

S. Etemad, P. Toliver, R. Menendez, J. Young, T. Banwell, S. Galli, and J. Jackel are with Telcordia Technologies, Red Bank, NJ 07701 USA (e-mail: jackel@research.telcordia.com).

P. Delfyett is with the College of Optics, UCF, Gainesville, FL 32816 USA.

C. Price and T. Turpin are with Essex Corp., Columbia, MD 21046 USA (e-mail: setemad@telcordia.com).

Digital Object Identifier 10.1109/LPT.2005.843692

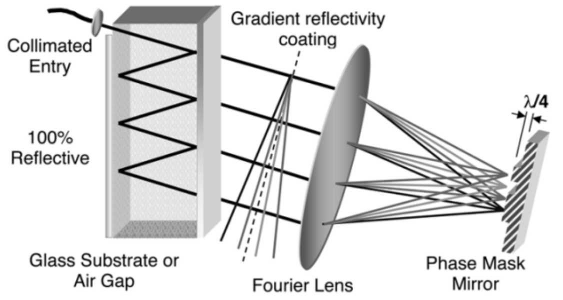

Fig. 1. The coder–decoder.

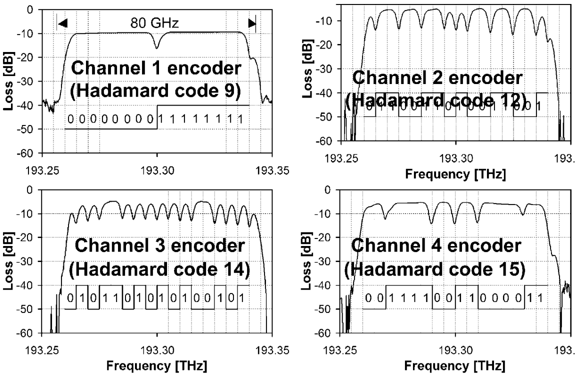

Fig. 2. Intensity transfer function of four coders. All frequencies are reflected back into the output fiber and only interference at [0, π] bin boundary reduces reflected output.

then a signal obtained by summing the phase-shifted frequency components of the modulated signal, or equivalently, by convolving the modulated optical signal at the input of the phase encoder with the inverse Fourier transform of the phase code.

Applying any of these orthogonal codes (except for the trivial case of Code 1, which leaves all phases unchanged) results in a temporal pattern which has zero optical power at the instant in time where the initial pulse would have had its maximum power. Decoding is accomplished by using a matched, complementary code; for the binary codes used here, the code is its own complement and consequently the coder and decoder are identical. The decoded signal has the pulses restored to their original position within the bit period and restores the original pulse shape. Decoding using an incorrect decoder results in a temporal pattern that again has zero optical power at the center of the bit period and the majority of the energy for that pulse is pushed outside the time interval where the desired pulse lies. The desired decoded signal can then be separated from all other users' signals by appropriate optical time gating.

Although this choice of orthogonal codes implies synchrony as a system requirement, since desynchronization will move unwanted optical power into the desired signal's time slot, careful code selection allows some relaxation of this requirement. Simulations indicate that for four simultaneous users transmitting at 2.5 Gb/s and using a suitably chosen set of four codes among the set 16 Hadamard codes of length 16, up to 15 ps of relative delay can be tolerated with a power penalty within 1 dB at a bit-error rate (BER) of 10^{-9}. Better resiliency to asynchronism may be achieved by using multiphase codes.

III. IMPLEMENTATION OF CODING

Phase coding of the individual spectral components requires a demultiplexer with sufficient resolution and path-length stability and a means of shifting phases independently for each frequency. Fig. 1 shows a coder–decoder based on a modified reflective geometry Essex Hyperfine optical demultiplexer [4], [5] and Fig. 2 shows its spectral response for codes 9, 12, 14, and 15, from the Hadamard-16 code set, as measured using a broad-band source; the phase shifts are shown below the spectrum. This device has a free spectral range of 100 GHz and a resolution of ~1 GHz. As Fig. 1 shows, all MLL lines are spectrally spread by the multipath glass substrate and imaged on the focal plane, from which they are reflected back to an output fiber. A phase mask at the focal plane shifts each line by an amount determined by a particular OCDMA code. The phase mask contains 16 sections representing the 16 frequency bins, each section recessed at 0 or $\lambda/4$ with respect to the focal plane representing 0 or π phase shift, respectively. Because of the finite spot size of the image at the focal plane, the effective bandwidth of the frequency bin is less than the bin spacing.

The sharp dips in Fig. 2 correspond to boundaries between two bins with different phase shifts where destructive interference occurs between the two oppositely phased halves of the light spot. The resolution of the OSA (0.01 nm, or approximately 1.245 GHz) reduces the apparent depth of these dips. Where adjacent bins have the same phase, there is no dip in the spectrum. This coder provides stable phase shifts; while thermal dimensional changes can shift optical paths, the *relative* path lengths for adjacent frequencies is unaltered.

This passive structure imposes no intrinsic power loss; although the current implementation has 5-dB loss, this can certainly be reduced. As the number of bins increases there is no increase in loss, and hence, this approach to coding has better scalability than time domain approaches such as fast frequency hopping [6].

The filter bandwidth narrowing affects the ability of the coder to process data, as opposed to an unmodulated pulse stream. When the coded signal carries data, the entire bandwidth of the modulated signal of a given MLL line must fit within the frequency bin as physically defined by the geometry of the phase encoder's focal plane. Simple ON–OFF keying at rates equal to the bin spacing (5 GHz) spreads the frequency into the unusable region between bins; thus, we need a modulation scheme with adequate bandwidth compression to ensure proper transmission. This is because the use of binary codes causes destructive interference at the [0, π] boundaries. We have demonstrated that ON–OFF key modulation at 2.5 Gb/s, using two pulses per bit from an MLL running at a pulse-repetition rate of 5 GHz satisfies this physical restriction. Alternative approaches using duo-binary or single sideband modulation for bandwidth compression will also ensure that the spectral constituents of the data-modulated signal stay within their respective frequency bins even at a data rate of 5 Gb/s. We note that when multiphase codes that do not exhibit 0-π phase transitions are used, the amplitude dips at the bin edges are reduced.

IV. EXPERIMENTAL RESULTS

For system integration, output of a 13-dBm Calmar laser is shared between four users, each with its own data stream and

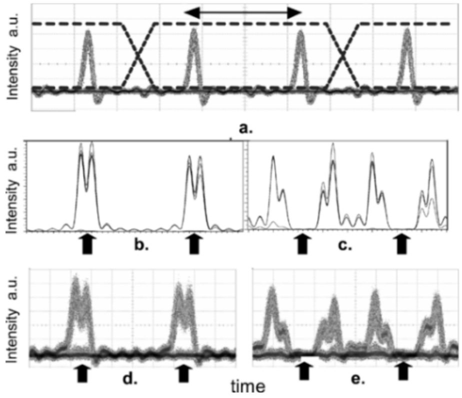

Fig. 3. (a) Input to coders, with two pulses per bit. Simulated output of (b) Coders 1 and (c) 2. Measured output of (d) Coders 1 and (e) 2. The arrow measures 200 ps.

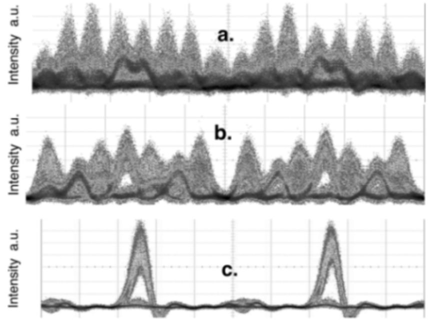

Fig. 4. (a) Four coded signals combined. (b) The same four after passing through Decoder 2. (c) Decoder output of (b) after time gating to isolate decoded channel.

external modulator which in turn is followed by its coder with a unique code. Output of the four coders are multiplexed into a fiber with a decoder capable of changing its code to match any one of the four transmitters. Output of the decoder is time gated to select the proper sender and reject the MUI from the other three and in turn fed to a optical–electrical receiver. Fig. 3 illustrates the measured time response of the coded data for each of the four codes. Fig. 3(a) shows the initial two pulses within one bit period, and Fig. 3(b)–(e) shows the outputs of two of the coders. For each code, the pulse energy has been distributed across the bit period by splitting into two or more pulses, with optical power at a minimum in the central portions of the bit period, indicated by the broad arrows in the figure, where the original uncoded pulses would have been present. In these, as in all time-domain measurements, the resolution of the measurements is limited by the 30-GHz response of the detector.

Fig. 4(a) shows the combination of four encoded signals. A decoded signal in the presence of three other codes is shown before gating in Fig. 4(b). The optical power associated with the interfering users is present but is displaced in time from the decoded data, which alone shows an eye opening. As a result, in the presence of multiple users, we use optical time-gating using a semiconductor optical amplifier-based TOAD [7] and a clock transmitted in a separate window to extract the desired correctly decoded pulse and to identify and extinguish the remaining MUI. BER was measured for the decoded and gated signal, when it was alone and in the presence of one, two, and three additional channels carrying independent data at 2.5 Gb/s.

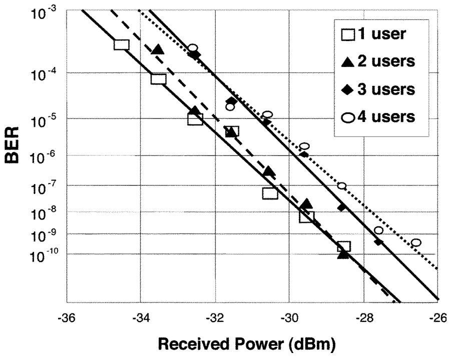

Fig. 5. Measured BER for Channel X when one, two, three, and four users are present as a function of power for the decoded and gated single user. Each user has an independent data stream. Small differences in fitted slopes result from measurement uncertainty.

In all cases, BER of less than 10^{-9} were obtained, as shown in Fig. 5, using a commercial SONET OC-48 receiver.

V. CONCLUSION

We have demonstrated for the first time a novel OCDMA coding and decoding method based on phase coding of tightly spaced phase-locked laser lines that is compatible with conventional WDM networking. This OCDMA system has been demonstrated to accommodate four simultaneous users at 2.5 Gb/s with BER $< 10^{-9}$. Measured performance of our experimental system shows good agreement with simulation results. Further simulation aids in the selection of optimal code sets and provides guidance for appropriate modulation formats to optimize system performance in the presence of MUI and transmission impairments. We have demonstrated a spectral efficiency of 12.5% (4×2.5 Gb/s in an 80-GHz window); simulation indicates that 50% spectral efficiency can be achieved with these coders with eight simultaneous users at 5 Gb/s, if duobinary modulation is used to limit spectral spreading. Since the C-band accommodates many such windows, this approach, applied to each window, can support more than 100 simultaneous users. Our simulation shows that the impairments due to nonlinear optical processes are suppressed in part due to reduced peak power, since coding spreads optical power across the bit period, which is much larger than the MLL pulse duration.

REFERENCES

[1] J. Shah, "Optical code division multiple access," *Opt. and Photon. News*, vol. 14, pp. 42–47, Apr. 2003.

[2] J. A. Salehi, A. M. Weiner, and J. P. Heritage, "Coherent ultrashort light pulse code-division multiple access communication systems," *J. Lightw. Technol.*, vol. 8, no. 3, pp. 478–491, Mar. 1990.

[3] S. Etemad, T. Banwell, S. Galli, J. Jackel, R. Menendez, P. Toliver, J. Young, P. Delfyett, C. Price, and T. Turpin, "Optical-CDMA incorporating phase coding of coherent frequency bins: Concept, simulation, experiment," in *Proc. OFC*, Los Angeles, CA, 2004, Paper FG5.

[4] "Optical tapped delay line," U.S. Patent 6 608 721.

[5] M. Shirasaki, "Large angular dispersion by a virtually imaged phased array and its application to a wavelength demultiplexer," *Opt. Lett.*, vol. 21, pp. 366–368, 1996.

[6] H. B. Jafar, S. LaRochelle, P.-Y. Cortes, and H. Fathallah, "1.25 Gbit/s transmission of optical FFH-OCDMA signals over 80 km with 16 users," in *Proc. OFC*, Anaheim, CA, 2001, Paper TuV3.

[7] P. Toliver, R. J. Runser, I. Glesk, and P. R. Prucnal, "Comparison of three nonlinear interferometric optical switch geometries," *Opt. Commun.*, vol. 175, pp. 365–373, 2000.