Optical-CDMA incorporating phase coding of coherent frequency bins: concept, simulation, experiment

Shahab Etemad, Tom Banwell, Stefano Galli, Janet Jackel, Ron Menendez, Paul Toliver, Jeff Young
Telcordia Technologies, Red Bank, NJ 07701
setemad@telcordia.com

Peter Delfyett
School of Optics/CREOL, UCF, Orlando, FL 32816

Craig Price, Terry Turpin
Essex Corporation, Columbia, MD 21046

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OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

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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 different set of challenges[1]. Here we describe the conceptual basis and initial results for a phase-frequency approach to OCDMA which is compatible with existing transparent reconfigurable optical networks. We use 16 equally spaced phase locked laser lines within an 80 GHz tunable window as frequency chips and phase encode each chip using a coder based on a novel ultrahigh resolution optical demultiplexer. Note that our approach has the advantage of discrete frequency lines and small tunable window compared to an earlier work that used the very broad optical bandwidth of an ultrashort pulse[2]. The encoding process consists of separating each of the frequency chips, shifting its phase by 0 or π, as prescribed by the choice of code, and recombining the frequency chips to produce the coded signal. In conventional wavelength division multiplexing (WDM) each one of 16 users would be statically assigned one line only. In our OCDMA system, every user uses all 16 lines but with different phase encodings. The result is a flexible network where codes, like telephone numbers, determine the connectivity. For example, statistical multiplexing allows a much larger number of total users than in the static WDM case, code exchange replaces wavelength exchange for rerouting, and the encoding obscures the data transmission for enhanced privacy. In this presentation we describe the key technologies that support this choice of OCDMA and the simulation studies that govern the choice of codes, define hardware design rules, and influence choice of modulation scheme; and we also present the initial experimental results that prove feasibility of this approach to OCDMA.

Key technologies: The OCDMA scheme we have explored requires a stable source of closely spaced phase-locked frequencies. This phase-locked comb, shown in Fig. 1, is generated by a mode-locked laser (MLL). The lines are the longitudinal modes of the MLL with a spacing equal to the pulse repetition rate, in this case 5 GHz. Their phase-

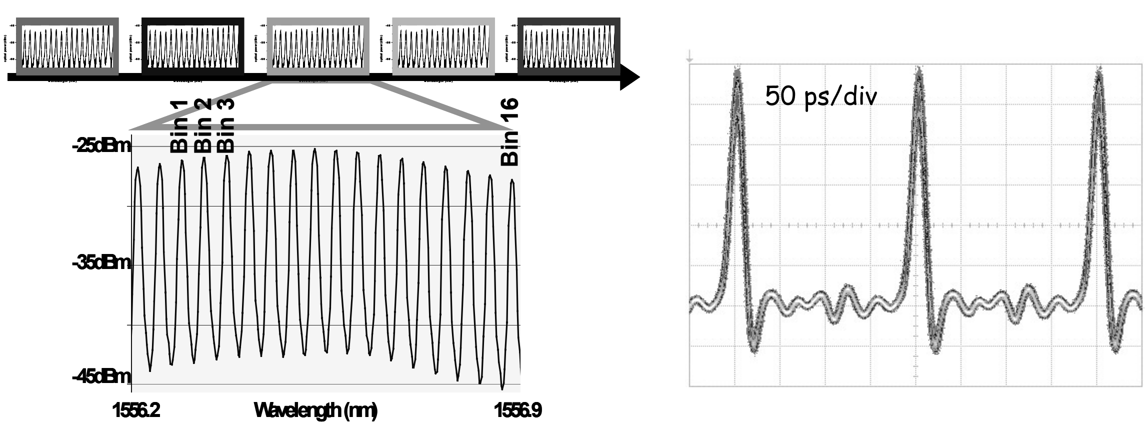


Fig. 1 Output of mode locked laser (a) The 5 GHz spaced comb within a tunable WDM window and (b) output pulses

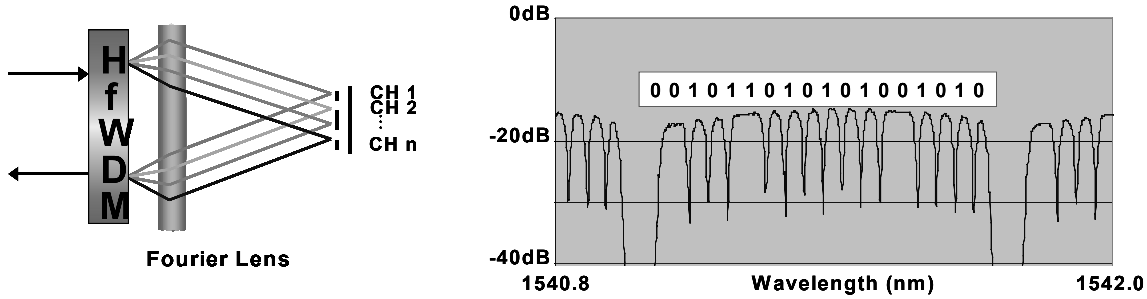
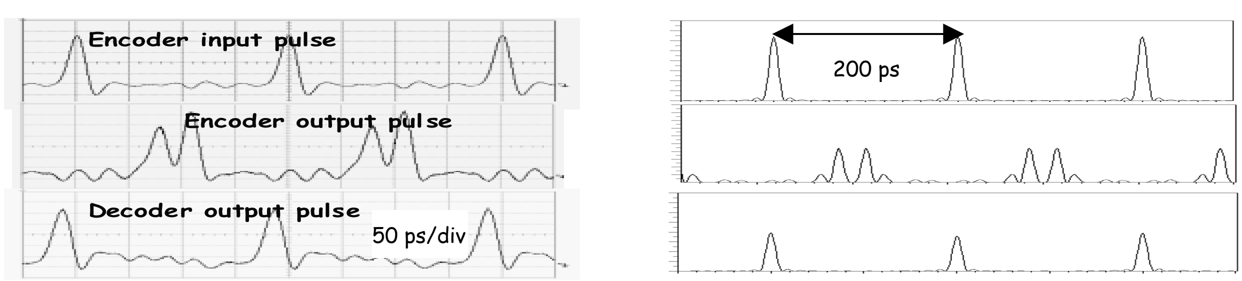


Fig. 2: The phase encoder/decoder: (left) schematic picture and (right) measured spectral transmission for code 14. The 0's and 1's represent –1 and 1 for the Hadamard codes, or 0 and π phase shifts.

locked addition generates the mode-locked pulse train with a pulse width inversely proportional to the spectral width of the window. The top section of Fig. 1a sketches multiple windows indicating the tunability of this source, which can be limited to a 80 GHz total spectral width using an optical bandpass filter within the laser cavity.

Phase coding of the individual spectral components requires a demultiplexer with sufficient resolution and a means of shifting phases for each frequency. Figure 2 shows the spectral response of a modified reflective geometry Essex *Hyperfine*™ optical demux [3] measured using a tunable laser. This device has a free spectral range of 80 GHz and a resolution of 5 GHz. All MLL lines are spectrally spread and imaged on the focal plane where they are reflected back to the output fiber; a phase mask at the focal plane shifts each line by an amount determined by the selected code. The phase mask contains 16 sections representing the 16 frequency bins, each section recessed at 0 or λ/4 with respect to the focal plane representing 0 or π phase shift, respectively. The sharp dips in Fig. 2b corresponds to boundaries between two bins with different phase shifts where destructive interference occurs between the two oppositely phased portions of the reflected interrogating laser line. The two wide dips represented masked areas that do not reflect; they and the first 2 bins on the left side are not used in the current coding process. Each user is identified by a code, a unique arrangement of phase shifts which are applied to the spectral lines of the modulated signal. We have chosen the set of Hadamard codes, which are orthogonal and binary codes, for initial implementation. Binary Hadamard codes are converted to phase codes by assigning to -1's and 1's phase shifts of 0 and π. The output of the phase encoder is then a signal obtained by convolving the modulated optical signal at the input of the phase encoder with the Inverse Fourier Transform of the phase code. Note that this process is fundamentally different from what is done in conventional optical or wireless DS-CDMA. Although the choice of orthogonal codes implies synchrony as a system requirement, careful code selection allows some relaxation of this requirement. For example, for four simultaneous users transmitting at 2.5 Gb/s and using Hadamard codes of length 16, up to 37.5 ps of relative delay can be tolerated with no performance degradation.

Experimental results: We have constructed a matched encoder-decoder pair with the decoder being capable of accommodating any of the masks corresponding to the 9^{th}, 12^{th}, 14^{th}, and 15^{th} codes from the Hadamard-16 code set. Figure 3 illustrates the measured and simulated time response of the mode-locked pulses from our MLL at three positions in a point-to-point test system: 1) before the encoder, 2) after the encoder and before the decoder, 3) and after the decoder. We note that between the coder and decoder, i.e., in the transmission fiber, the pulse energy has been shifted to a "wrong" time slot and split into two pulses. The figure shows results for code 14; the pattern will be different for different codes. However, irrespective of the choice of a code identifying a user, the carrier pulse train is retrieved at the "right" time slot after the decoder.



(a) (b)

Fig. 3 Unmodulated signal pulse train before & after encoder, and after decoder, (a) measured results and (b) simulation

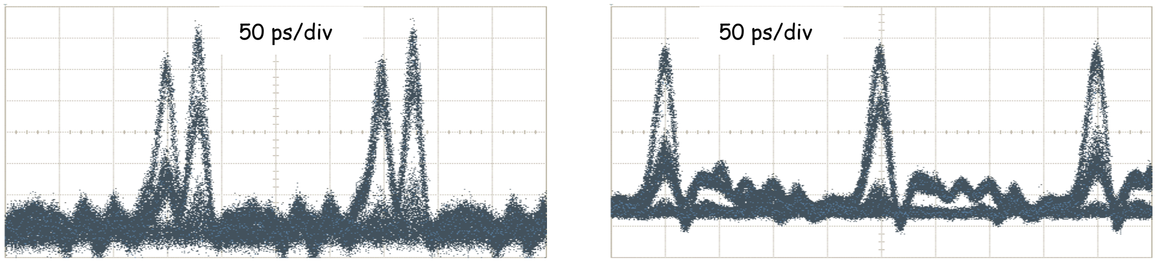


Fig. 4 Coded (left) and decoded (right) data at 2.5 Gb/s.

Modulation formats and multiuser interference: Our initial measurements of Fig. 3 demonstrate that it is possible to code and decode a pulse stream. Two other issues are important for OCDMA: multi-user interference, and modulation formats suitable for various data rates. The above results (Fig. 3) describe the response of our OCDMA system to an unmodulated carrier. 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. Because of the finite spot size of the image at the focal plane, the usable bandwidth is significantly less than the spacing of the frequency bins. Thus we need a modulation scheme with adequate bandwidth compression to ensure proper transmission. We have studied alternative modulation schemes in simulation and have demonstrated that on-off key modulation at 2.5 Gb/s using two pulses per bit from a MLL running at a pulse-repetition rate of 5 GHz satisfies this physical restriction. Alternative approaches using duo-binary modulation for bandwidth compression 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. Fig. 4 below shows the first demonstrations of coded and decoded data, using 5 GHz frequency bins to code 2.5 Gb/s data. The results indicate that the frequency bins are adequately wide to carry this data rate.

Fig. 5 shows a simulation of a decoded user in the presence of three other users with different codes. The optical power associated with the interfering users is present but is displaced in time from the decoded data, which alone shows a clear eye. As a result, in the presence of multiple users, we need to use time-gating procedures to identify and isolate the "right" time slot, identified by the superimposed boxes in Fig. 5. Our simulations show that the open eye in the optical time gating window corresponds to a BER well below our target of BER $< 10^{-9}$ even in the presence of network impairments.

Conclusions: We have demonstrated for the first time a novel optical CDMA coding and decoding method, based on phase coding of coherent frequency chips, that is compatible with conventional WDM. Measured performance shows good agreement with simulation. Further simulation provides guidance for appropriate modulation formats and predicts adequate system performance in the presence of multi-user interference.

[1] Jagdeep Shah, "Optical Code Division Multiple Access", Optics and Photonics News, Volume 14, page 42-47, April 2003.
[2] Jawad A. Salehi, Andrew M. Weiner, Jonathan P. Heritage, "Coherent Ultrashort Light Pulse Code-Division Multiple Access Communication Systems", J. of Lightwave Technologies, Vol. 8, page 478, March 1990.
[3] For the physical concept behind the operation of the Hyperfine device see US Patent #6,608,721

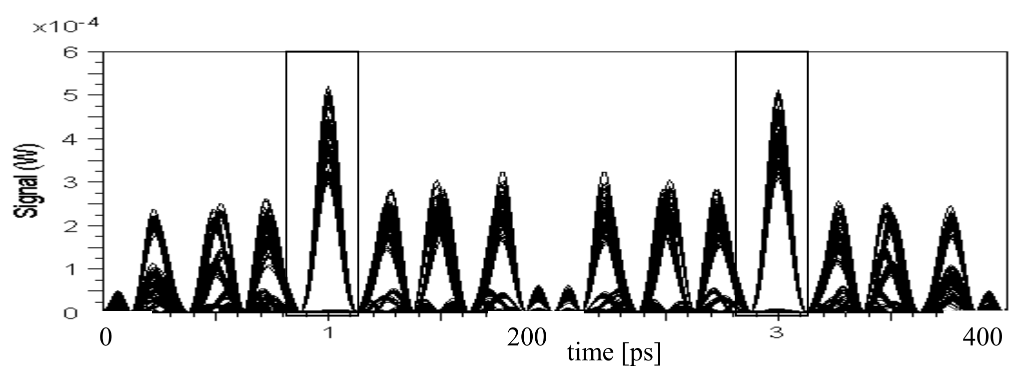


Fig. 5 Decoded code 9, with codes 12, 14, 15 also present, with half rate (2.5 Gb/s) modulation on all codes (simulation)