

# Coherent Heterodyne OCDMA with Sourceless and Colorless Receivers

Yi Yang, *Life Senior Member, IEEE*, Jacob B. Khurgin, Mark Foster, and A. Brinton Cooper III

**Abstract**—We present a new, coherent, heterodyne OCDMA scheme that conveys the signal and reference to each user in a multiple access network via one fiber. The receiver is sourceless and colorless. Bit error rate performance is characterized as a function of system parameters under various conditions.

## I. INTRODUCTION

THE passive optical network (PON) has been identified [0] as an indispensable solution to the bottleneck posed by the access portion of today's networks. Optical code division multiple access (OCDMA) is an attractive PON candidate because it offers soft capacity on demand, freedom from MAC layer protocols, support for security, minimal multiple access interference (MAI) and beat noise, easy upgrade of any power-splitter-based network, and sourceless/colorless optical network units (ONUs) at user premises [1]. However, most OCDMA schemes suffer from excessive speckle and MAI because encoded signals are not truly orthogonal at the receiver and because the receiver does not truly cancel MAI but merely spreads it across time and frequency, creating excessive speckle.

Spectrally encoded OCDMA can be implemented by spectral phase encoding (SPE) or spectral amplitude coding (SAC) and in homodyne or heterodyne configurations. Our previously proposed SPOT<sup>1</sup> [2] is a truly coherent homodyne SPE OCDMA that cancels MAI in a phase/polarization diversity receiver that is superior to those of earlier SPE designs [3-5]. Heterodyne SAC OCDMA with line spacing at the bit rate [6] seems to suffer from marginal spectral efficiency. To mitigate the accumulation of excessive MAI, [7] proposed a multi-wavelength local oscillator for beat noise minimization; however this approach offers unnecessary cost and complexity and is neither sourceless nor colorless. Furthermore, SAC designs are not truly coherent.

Below, we propose coherent, SPE heterodyne OCDMA that offers performance comparable to [2] with an inexpensive receiver design and use of a single downlink fiber. The design is sourceless, colorless, resource efficient, and free of MAI.

## II. SYSTEM MODEL

### A. System Description

A single mode-locked laser in the *optical line terminal* (OLT, Fig. 2) is the source for two flattened (for orthogonality [?], [?]) and interleaved spectral combs that are separated

Authors are with the Department of Electrical & Computer Engineering, The Johns Hopkins University, Baltimore, MD 21218

<sup>1</sup>Spectral...

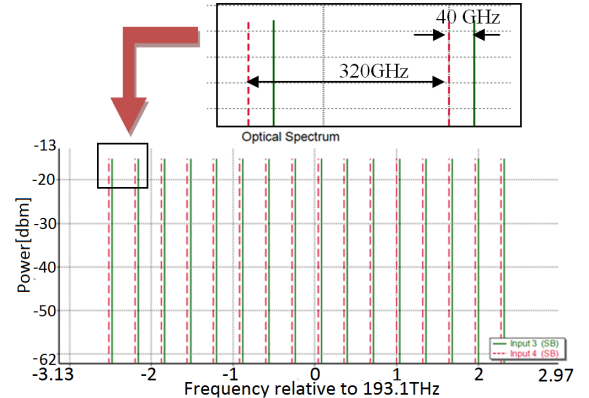


Fig. 1. Spectral combs for encoded signals and unencoded reference.

in frequency by  $\Delta\omega$ , the intermediate frequency (IF) of the heterodyne receiver and  $2\pi \times$  the information rate of the system (Fig. 1). For each of  $M$  users, a copy of the first comb (dashed in Fig. 1) is encoded with a unique *signature sequence* and, with the second unencoded comb (solid lines), is conveyed over a single fiber<sup>2</sup> to the receiver's *optical network unit* (ONU, Fig. 2) where the reference comb is encoded with the phase sequence corresponding to the desired user's signal. The ensemble is mixed in a balanced detector (BD) and the output is filtered at  $2\Delta\omega$ . For uplink transmission, the received reference comb is encoded, modulated, and returned over a second fiber. Thus, all optical signals in the system are derived from a single mode-locked laser (MLL) (as in [2]) and use the same optical combs, resulting in sourceless/colorless operation.

Let the  $m^{\text{th}}$  users' comb be  $\{\omega_n^m\}_{n=1}^N$ , and the reference comb be  $\{\omega_n^r\}_{n=1}^N$ . Then  $\Delta\omega = \omega_n^m - \omega_n^r$ . The transmitted reference comb is  $r(t) = \sum_{n=1}^N e^{j\omega_n^r t}$  and the  $m^{\text{th}}$  user's transmitted signal is  $s_m(t) = A_m \sum_{n=1}^N c_n^m e^{j\omega_n^m t}$  where  $\{c_n^m\}_{n=1}^N$  is the  $m^{\text{th}}$  signature sequence and  $A_m$  is the  $m^{\text{th}}$  user's data symbol.

### B. Dispersion

When the reference is encoded with the  $m^{\text{th}}$  user sequence, the output of the BD/filter is

$$s_{IF}(t) = \sum_{n=1}^N c_n^m c_n^m e^{j\Delta\phi_n} = \sum_{n=1}^N c_n^m c_n^m (1 + \Delta\phi_n) \quad (1)$$

<sup>2</sup>Due to the use of a single fiber, the scheme is not polarization sensitive.

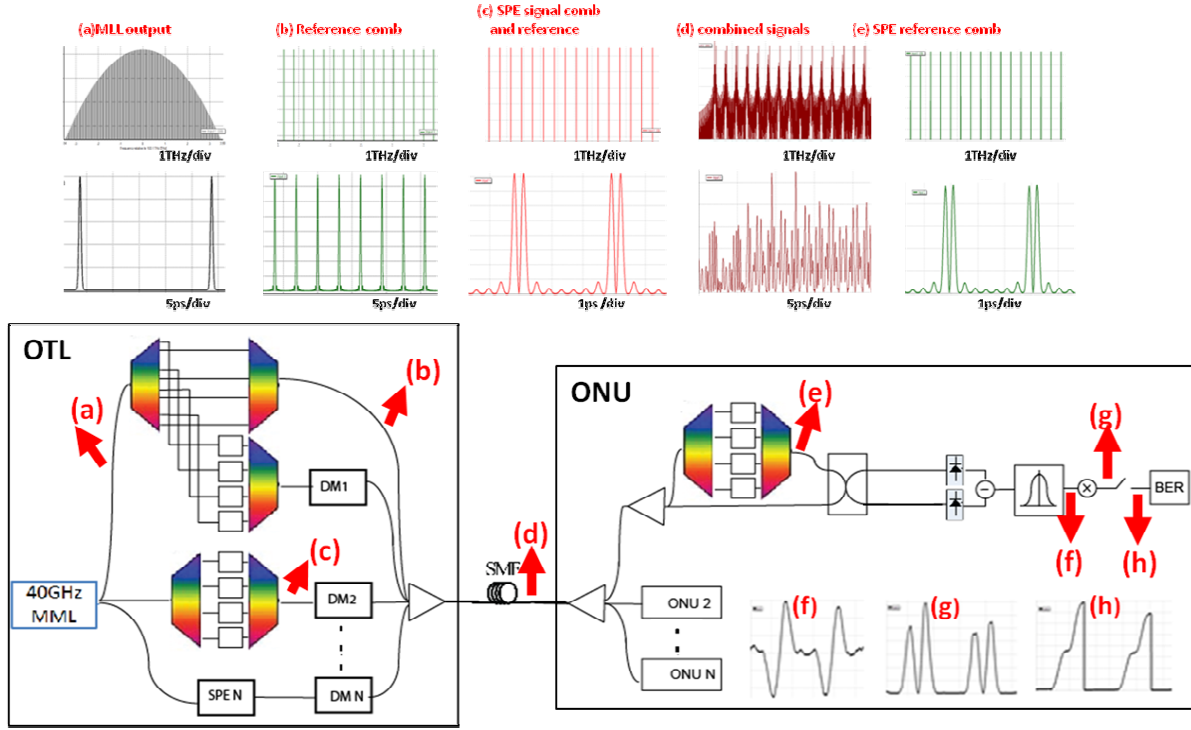


Fig. 2. Coherent SPE heterodyne OCDMA and key waveforms

where  $\Delta\phi_n$  is the dispersion-induced phase shift on the  $n^{\text{th}}$  spectral line. For any  $n$ ,

$$\Delta\phi_n = \phi_n(\omega_n^r) - \phi_n(\omega_n^s) \quad (2)$$

$$= -[k(\omega_n^r) - k(\omega_n^s)] \cdot L \quad (3)$$

$$= -\Delta k \cdot L \quad (4)$$

where  $k(\omega)$  is the wavenumber. We expand  $k(\omega)$  about an arbitrary  $\omega_0$  over each of the combs and subtract the two expressions to get

$$k_n^r = k(\omega_0) + \frac{\partial k(\omega_0)}{\partial \omega} (\omega_n^r - \omega_0) + \frac{1}{2} \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_n^r - \omega_0)^2$$

$$k_n^m = k(\omega_0) + \frac{\partial k(\omega_0)}{\partial \omega} (\omega_n^m - \omega_0) + \frac{1}{2} \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_n^m - \omega_0)^2$$

$$\Delta K \approx \frac{\partial k(\omega_0)}{\partial \omega} \cdot \Delta\omega + \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \cdot \Delta\omega \cdot \omega_n^m - \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \omega_n^m \cdot \Delta\omega$$

$$\Delta\phi_n = \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \omega_n^m \Delta\omega \cdot L \quad (5)$$

### C. Relative Delay

Let  $\Delta\tau_d$  be the frequency-independent delay between the reference and signal combs. Then the relative phase shift in the balanced detector between the  $n^{\text{th}}$  lines of the combs is

$$\begin{aligned} \Delta\phi_{n,d} &= \Delta\tau_d(\omega_n^r - \omega_n^s) \\ &= \Delta\tau_d(n-1)\Delta\omega \end{aligned}$$

## III. SIMULATIONS AND COMPARISONS

Here we focus on the synchronous downlink and its transmitted set of pairwise orthogonal signals. In the simulation model (Fig. 2), two 16-line combs are obtained from a 1550 nm, 500 fs, 40 Gb/s MLL and are encoded with length 16 Hadamard sequences. Pseudorandom data is modulated at 40 Gb/s using OOK. The IF is 40 GHz, and the post detection filter bandwidth is 79 GHz (Fig 2(f)). We focus our analysis on the two factors that may cause the most severe signal-to-noise ratio (SNR) degradation: total dispersion and delay between the signal and reference. Dispersion affects orthogonality by stretching the signal and reference in the fiber and increases

with the number of users due to added MAI caused by the non-orthogonality. The simulated performance degradation from residual dispersion is shown in Fig 4. Asynchronism (relative delay) between encoded signal and reference or between two user signals can occur in the distinct signal pathways of the optical circuitry, again rendering the signals pairwise non-orthogonal; the non-zero crosscorrelation products [9] produce MAI which increases with the number of users and is zero only when interferers are pairwise orthogonal and, therefore, synchronous. To study the effects of asynchronism, delay is introduced before the encoded reference comb is sent to the coupler (at point B, Fig. 2). The simulated performance degradation from asynchronism is displayed in Fig. 5.

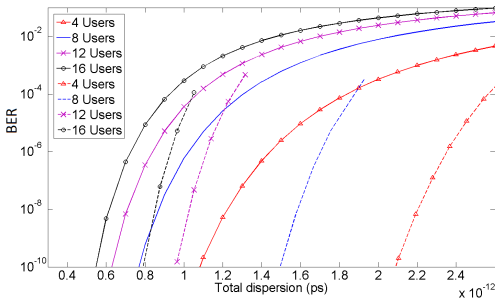


Fig. 3. Analytic and Simulated Performance vs Dispersion

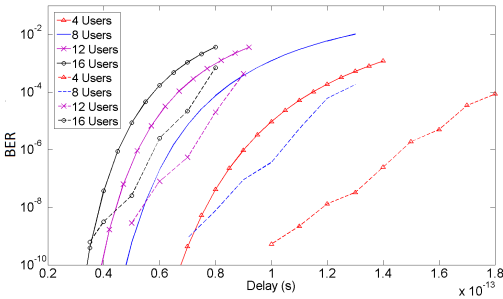


Fig. 4. Analytic and Simulated Performance vs Relative Delay

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## APPENDIX: DERIVATIONS

When the reference is encoded with the  $m^{th}$  user sequence, the output of the BD/filter is

$$s_{IF}(t) = \sum_{n=1}^N c_n^{(m)} c_n^m e^{j\Delta\phi_n} = \sum_{n=1}^N c_n^m c_n^m (1 + \Delta\phi_n) \quad (6)$$

where  $\Delta\phi_n$  is the dispersion-induced phase shift on the  $n^{th}$  spectral line. For any  $n$ ,

$$\Delta\phi_n = \phi_n(\omega_n^r) - \phi_n(\omega_n^m) \quad (7)$$

$$= -(k_n^r - k_n^m) \cdot L \quad (8)$$

$$= -\Delta k \cdot L \quad (9)$$

where  $k_n^r$  and  $k_n^m$  are the frequency dependent wavenumbers at the  $n^{th}$  lines of the reference and the  $m^{th}$  user's combs respectively. **(Maybe we need to drop  $m$  since the lines are at the same frequencies for all users?)** We expand each  $k$  about arbitrary  $\omega_0$  and subtract the two expressions to get

$$k_n^r = k(\omega_0) + \frac{\partial k(\omega_0)}{\partial \omega} (\omega_n^r - \omega_0) + \frac{1}{2} \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_n^r - \omega_0)^2$$

$$k_n^m = k(\omega_0) + \frac{\partial k(\omega_0)}{\partial \omega} (\omega_n^m - \omega_0) + \frac{1}{2} \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_n^m - \omega_0)^2$$

$$\Delta k = k_n^r - k_n^m$$

$$= \frac{\partial k(\omega_0)}{\partial \omega} \cdot \Delta\omega$$

$$+ \frac{1}{2} \frac{\partial^2 k(\omega_0)}{\partial \omega^2} [(\omega_n^r)^2 - (\omega_n^m)^2 - 2\omega_0 \Delta\omega]$$

Now

$$(\omega_n^r)^2 - (\omega_n^m)^2 = \Delta\omega(\omega_n^r + \omega_n^m) \sim \Delta 2\omega(2\omega_n^m)$$

So,

$$\Delta k \approx \frac{\partial k(\omega_0)}{\partial \omega} \cdot \Delta\omega + \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \cdot \Delta\omega \cdot \omega_n^m - \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \omega_n \cdot \Delta\omega$$

Substituting  $\Delta k$  into (9) gives

$$\Delta\phi_n = - \left( \frac{\partial k(\omega_0)}{\partial \omega} \cdot \Delta\omega + \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_n^m \Delta\omega) + \frac{\partial^2 k(\omega_0)}{\partial \omega^2} (\omega_0 \Delta\omega) \right) \cdot L$$

But the first and the third term are constant over  $\omega_n^m$ , so do not contribute to the phase growth across the comb. Therefore,

$$\Delta\phi_n = \frac{\partial^2 k(\omega_0)}{\partial \omega^2} \omega_n^m \Delta\omega \cdot L \quad (10)$$