Coherent Optical CDMA with low MAI

A. Brinton Cooper III, Jacob B. Khurgin, Shuangmei Xu, Jin U. Kang
Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, MD 21218
{abcooper, jakek, jkang}@jhu.edu

Abstract. Spectrally phase-coded optical code division multiple access (OCDMA), demodulated with phase and polarization diversity devices, exhibits high spectral efficiency and low Multiple Access Interference (MAI). Use in a passive optical network (PON) is discussed.

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Speckle noise [2], optical time gating [3], and nonlinear detection [4] limit OCDMA to the suboptimal. Recently [1] a new method for interference-cancelling, phase coherent demodulation of spectrally encoded OCDMA was shown to achieve good spectral efficiency and low MAI without using expensive nonlinear opticals or phase locked loops. The phase and polarization diversity (PPD) [5] multiple access receiver is largely free from MAI and beat noise. A single laser at the root of an optical access tree network [6] provides a stable optical pulse train that is distributed through the network to generate all uplink and downlink signals (Fig. 1). Gain equalization [7], flattens the optical comb spectrum, which is split into M user streams. Each of M combs is spectrally demultiplexed into two combs, one of which is phase encoded[1] by a sequence from an orthogonal set [9] and data modulated using on-off keying (OOK). This set of M downlink signals and the other uncoded comb are conveyed via a single fiber through the network to each user's *optical network unit* (ONU). A second fiber conveys the unencoded downlink comb to each ONU where it is phase encoded with the desired signal sequence as a local reference for coherent demodulation. Similarly, each ONU encodes the second comb with its unique sequence, data modulates this encoded comb, and sends this uplink signal to the root via the second fiber. The downlink signal is $s_m(t) = S_m c_m(t)$ where S_m is the data bit and the encoded downlink comb is $c_m(t) = \sum_{n=-N/2}^{N/2-1} C_m^{(n)} e^{j\omega_n t},\ m = 1, 2, \ldots, M,\ \omega_n = \omega_0 + 2\pi n/T,\ C_m^{(n)} = \pm 1$ for BPSK, N is the sequence length, and T is the bit interval. The encoded LO and the input beams each are split into orthogonal polarizations and the phase of each LO polarization beam is shifted by $\pi/2$. Each LO beam is mixed with each input beam in the PPD combiner to remove phase and polarization fluctuations between the LO and the received signal. The electric fields input to the top detector's hybrid are $E_S(t) = \sqrt{P_S} \cos\theta_S \sum_{m=1}^{M} S_m c_m(t) e^{j\phi_m}$ and $E_{LO}(t) = \sqrt{P_{LO}} \cos\theta_{LO} c_{LO}(t) e^{j\phi_{LO}}$ where M is the number of users, S and LO denote channel and local oscillator signals, respectively; P and ϕ are optical power and phase, respectively; and θ is the angle between the polarization plane and the x axis. Encoded combs $c_m(t),\ m = 1, \cdots, M$ are pairwise orthogonal ($i.e.,\ \frac{1}{T}\int_0^T c_m(t) c_s^*(t) dt = e^{j(\phi_m - \phi_s)} \sum_{n=1}^{N} C_m^{(n)} C_s^{(n)*}$) if the received user signals are completely synchronized. A synchronous system has no MAI since the coded signals remain orthogonal. However, impairments, component variations, and asynchronous reception can compromise orthogonality and increase MAI. We can split the delay between the LO and the m^{th} user signal into two parts: $\Delta t_{m-LO} = \delta t_{m-LO} + (\phi_m - \phi_{LO})\omega_0^{-1}$. The term $\Delta\phi_m \omega_0^{-1} = (\phi_m - \phi_{LO})\omega_0^{-1}$ is fixed by the

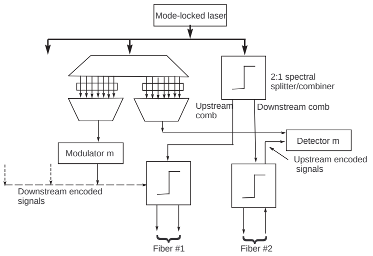

Figure 1: Root's node optical line termination unit

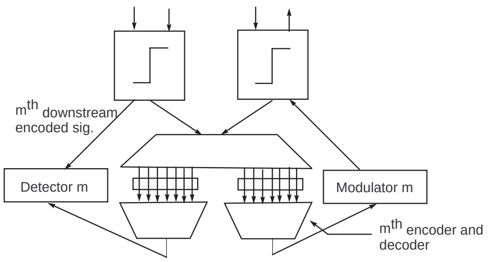

Figure 2: User's optical network unit

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[1] The encoder is essentially the one used by Weiner[8].

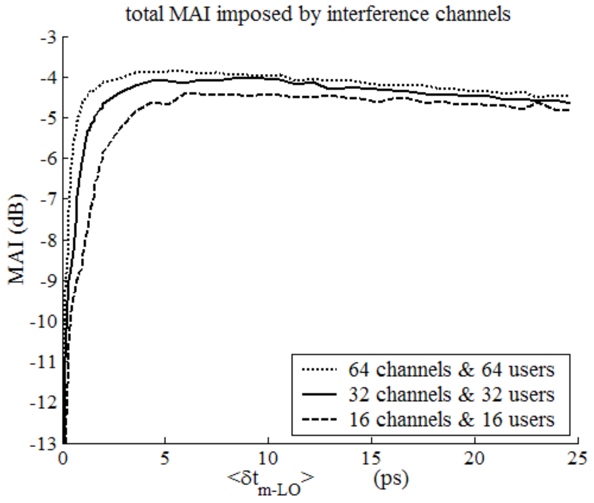

Figure 3: MAI for systems of N=64, 32, and 16 users.

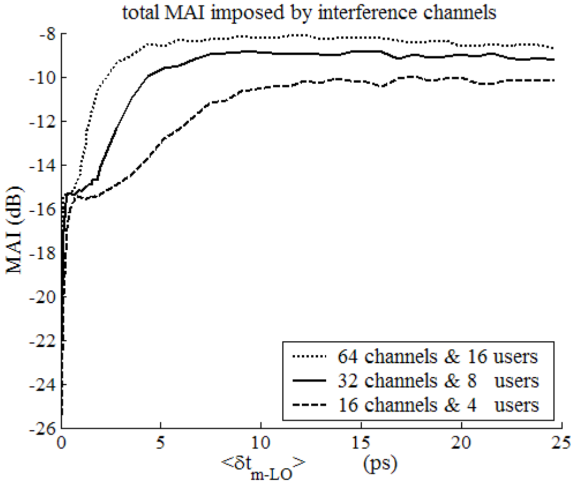

Figure 4: MAI for M=N/4 users.

PPD combiner design. The larger term $\delta t_{m-LO} = 2\pi\mathcal{I}\omega_0^{-1}$ represents an integer number $\mathcal{I}$ of carrier periods and produces MAI, as it compromises orthogonality (1). Because the system is bit asynchronous, at time

$$\frac{1}{T}\int_0^T c_m(t-\delta t_{m-LO})c^*_{LO}(t)dt = \frac{1}{T}e^{j\Delta\phi_m}\sum_{n=-N/2}^{N/2-1} C_m^{(n)} \sum_{\ell=-N/2}^{N/2-1} C_{LO}^{*(\ell)} \cdot \int_0^T e^{j(\omega_n-\omega_\ell)t}e^{j\omega_n\delta t_{m-LO}}dt. \tag{1}$$

k the integral over T involves two adjacent data symbols S_m^{k-1} and S_m^k, and the m^{th} user's signal must contain 2 terms (2). Substituting $s_m(t)$ into (1) gives the MAI on the m^{th} user(3). When signals are fully

$$s_m(t) = \begin{cases} e^{j\Delta\phi_m}S_m^{k-1}c_m(t-\delta t_{m-LO}), \ 0<t<\delta t_{m-LO} \\ e^{j\Delta\phi_m}S_m^{k}c_m(t-\delta t_{m-LO}), \ \delta t_{m-LO}<t<T \end{cases}. \tag{2}$$

synchronized, orthogonality assures that the MAI is essentially zero[2]. For *fully loaded* ($M = N$) systems of *asynchronous* 10 Gb/s users, Fig. 3 shows the relative MAI based upon (3). MAI improves considerably

$$MAI_m = e^{j\Delta\phi_m}S_m^{k-1}\int_0^{T-\delta t} c_m(t-\delta t)c^*_{LO}(t)dt + e^{j\Delta\phi_m}S_m^{k}\int_{T-\delta t}^{T} c_m(t-\delta t)c^*_{LO}(t)dt. \tag{3}$$

under partial loading as shown in Fig. 4. Using a single laser and accurately controlling the encoder-decoder distances to $\sim 1ps$ insures a synchronous downlink and a fully loaded spectral efficiency of nearly 1.0 b/Hz. The data rate of the asynchronous uplink is lower, so error control coding and/or exclusive time slot assignment can permit a partially loaded system to achieve useful bit error rates and a spectral efficiency approaching 0.25 for $M = N/4$. Or mode locked pulses can be distributed on a separate fiber for both synchronization and LO source, an attractive scheme for ring networks [1].

4 References

[1] A.B. Cooper III, J.B. Khurgin, and J.U. Kang, "Phase and polarization diversity for OCDMA," CLEO06, 2006.

[2] C. Lam *et al.*, "Experimental demonstration of bipolar optical CDMA system using a balanced transmitter and complementary spectral encoding," *IEEE Photon. Tech. Ltrs.*, vol. 10, Oct. 1998.

[3] E.D.J. Smith, *et al*, "Performance enhancement of spectral-amplitude coding optical CDMA using pulse-position modulation," *IEEE Trans. Commun.*, **46**, pp1176-85 (1998).

[4] V.J. Hernandez, *et al*, "Spectral phase-encoded time-spreading (SPECTS) optical code-division multiple access for terabit optical access networks," *J. Lightwave Technol.,* **22**, pp 2671-9, (2004).

[5] L. Kazovsky, "Phase and polarization-diversity coherent optical techniques," *IEEE J. Lightwave Technol.,* Feb 1989.

[6] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength division multiplexed passive optical network (WDM-PON) technologies for broadband access: a review," *J. Optical Networking*, vol. 4, pp 737-58, 2005.

[7] M. Rochette *et al.,* "Gain equalization of EDFAs with Bragg gratings," *IEEE Photon. Tech. Ltrs.,* vol. 11, 1999.

[8] A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," *Rev. Sci. Instrum.,* vol. 71, May 2002.

[9] C.L. Liu, *Introduction to Combinatorial Mathematics,* McGraw-Hill,1968, New York.

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[2] A forthcoming paper will discuss the use of asynchronously orthogonal sequences.