Coherent Optical CDMA with low MAI

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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 optics 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 N orthogonal sets [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 phase and polarization diversity devices, exhibits high spectral efficiency and low MAI 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 $c_m(t) = \sum_{n=-N/2}^{N/2} C_m^{(n)} e^{j\omega_n t}, m = 1, 2, \ldots, M$, $\omega_n = \omega_0 + 2 \pi n / T$, $C_m^{(n)} = \pm 1$ 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 $E_S(t) = \sqrt{T_S} \cos \theta_S \sum_{m=1}^{M} S_m c_m(t) e^{j\phi_m}$ and $E_{LO}(t) = \sqrt{T_{LO}} \cos \theta_{LO} c_{LO}(t) e^{j\phi_{LO}}$ where $M$ is the number of users, $S$ and $LO$ denote channel and local oscillator signals, respectively; $P$ and $\phi$ are optical power and phase, respectively; and $\theta$ is the angle between the polarization plane and the $x$ axis. Encoded combs $c_m(t), m = 1, \ldots, M$ are pairwise orthogonal (i.e., $\frac{1}{T} \int_0^T c_m(t)c_n^*(t) dt = e^{j(\phi_m - \phi_n)} \sum_{n=1}^{N} C_m^{(n)} C_n^{(n)}$) if the

Figure 1: Root’s node optical line termination unit

Figure 2: User’s optical network unit

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: $\Delta t_m - \Delta t_m - \Delta \phi_m - (\phi_m - \phi_{LO})\omega_0^{-1}$. The term $\Delta \phi_m \omega_0^{-1} = (\phi_m - \phi_{LO})\omega_0^{-1}$ is fixed by the

$^1$The encoder is essentially the one used by Weiner [8].
PPD combiner design. The larger term \( \delta t_{m-LO} = 2\pi T \omega_c^{-1} \) represents an integer number \( I \) of carrier periods and produces MAI, as it compromises orthogonality (1). Because the system is bit asynchronous, at time

\[
\frac{1}{T} \int_0^T c_m(t - \delta t_{m-LO}) e^{j \Delta \phi_m} dt = \frac{1}{T} \sum_{n=-N/2}^{N/2-1} C_m^n e^{j \sum_{\ell=-N/2}^{N/2-1} C_{\ell,LO}^{(n)} \int_0^T e^{j(\omega_m - \omega_c) t} e^{j \omega_c \delta t_{m-LO}} dt. \tag{1}
\]

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 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 under partial loading as shown in Fig. 4. Using a single laser and accurately controlling the encoder-decoder distances to \( \sim 1 \) ps 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


\(^2\) A forthcoming paper will discuss the use of asynchronously orthogonal sequences.