Painless fully orthogonal coherent OCDM

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Abstract: Coherent phase coding and phase and polarization diversity detection offer realistic implementation of fully orthogonal large spectral density Optical Code Division Multiplexing (OCDM) that is completely free of multiple access interference and speckle noise.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber Optics Communications.

1. Introduction

The potential for OCDM to increase system capacity, security, and flexibility is significantly limited by multiple access interference (MAI) [1]. In RF wireless communications, CDM achieves spectral efficiencies that exceed, by orders of magnitude, those of fiber OCDM because the RF receiver recovers the transmitted data via coherent correlation processing of the time domain BPSK chip sequence. Direct detection optical systems destroy phase, precluding coherent processing. In principle, modulating the phase and/or frequency of an optical pulse train with the same orthogonal sequence sets results in lower levels of MAI than are possible in current designs. However, phase coherent correlation processing of spectrally encoded OCDM faces the challenges of realizing an optical phase locked loop and compensating for polarization fluctuations in the received signal as well as phase noise in the transmitter and local oscillator (LO).

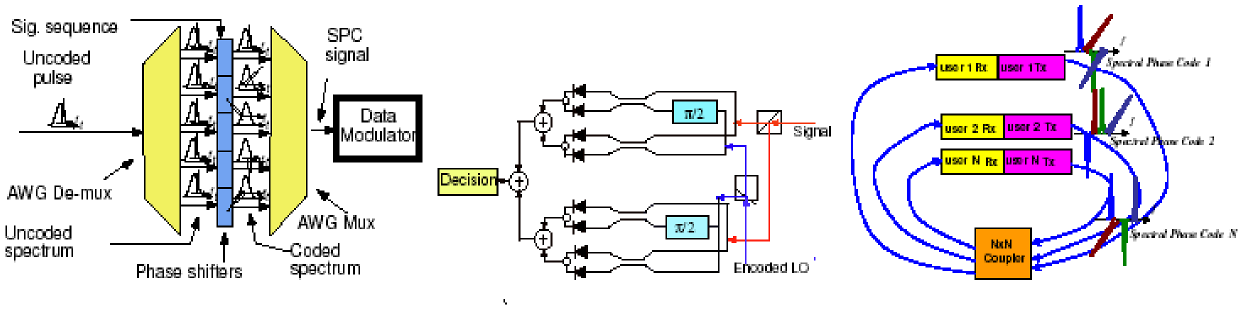
A number of techniques that achieve a certain degree of orthogonality without requiring coherent detection have been proposed and implemented. Using complementary spectral encoding and balance detection in [1] achieved transmission of two OCDM channels, but it had been noticed that when the direct-detection scheme is used with either a noncoherent or a coherent source the number of users is severely decreased by speckle noise originating in optical beat interference (OBI) between the users; e.g., fewer than 10×1 Gbits/s users can be supported even at a relatively high received optical power of -20 dBm [2]. In the popular alternative scheme the orthogonality in direct detection is achieved by passing the received signal through an encoder using the correct code, giving a sharp peak that can be discerned by a very fast, nonlinear peak detector (or by a nonlinear time gating). In fact, usefully low bit error rates have been demonstrated for optical phase coding with such a detector [3] but the MAI in that scheme is still very large because interfering codes produce a large background level. Hence, the spectral efficiency achieved in [3] was less than 0.01bps/Hz. That and the sheer complexity of nonlinear detection makes this scheme a poor candidate for such applications as passive optical networks (PON). Most recently it has been proposed to reduce the OBI by using heterodyne detection [4] where the OBI level is dwarfed by the interference between the signal and local oscillator (LO). However, the OBI level is still substantial in such a scheme, resulting in a large number of expensive optical components for each user.

In this work we propose a fully orthogonal coherent OCDM scheme that requires neither sophisticated nonlinear optical elements nor phase tracking, yet achieves high spectral efficiency and matches other performance metrics associated with CDM. This system can be realized in a compact, low cost design and is especially targeted for PONs

2. Operating principle of the proposed spectral phase coding and diversity decoding scheme

At the transmitter, an Arrayed Waveguide Grating (AWG) demultiplexer (Fig 1a) spatially decomposes the line spectrum (Fig. 2a) of a rate ($1/T$) stream of duration T_d optical pulses. The central N out of $2T/T_d$ spectral lines in the main lobe are BPSK encoded (using an array of slow phase modulators, *e.g.,* thermo-optical) by a signature sequence from a pairwise orthogonal set. An AWG multiplexer recombines the encoded spectrum into a time spread pulse of duration $\leq T$ (Fig. 2). This pulse sequence is then modulated with an OOK data stream. ***This encoding scheme is not substantially different from [3] – the novelty lies in the phase and polarization detection scheme using an optical hybrid (Fig.2a)***

In the receiver, received and identically SPC-encoded LO signals are split into oppositely polarized components. A phase and polarization diversity (PPD) [5] correlator (Fig. 1b) removes phase and polarization fluctuations between the LO and the signal. Each component of the received signal is mixed with



a. SPC enc/dec b. PP diversity c. SPC in a ring LAN

Fig.1 OCDM implementation using spectral phase coding and PP diversity

delay-orthogonal versions of the LO in a set of balanced detectors that integrate over each bit; hence, over each bit interval, full homodyne detection is achieved, offering much lower levels of MAI than in present OCDM receivers, thereby achieving competitive degrees of concurrency. The optical powers at each of eight detectors in PPD receivers are

$$P_{1-8} = \pm\frac{1}{4\sqrt{2}}\sqrt{P_{LO}P_S}\sum_j^M S_j \begin{Bmatrix}\cos\varphi_{j,LO}\\ \sin\varphi_{j,LO}\end{Bmatrix}\begin{Bmatrix}\cos\theta_j\\ \sin\theta_j\end{Bmatrix}\sum_k^N c_j^k c_i^{k*} + \frac{1}{8}P_{LO} +$$
$$+\frac{1}{4}P_S\sum_j^M\begin{Bmatrix}\cos^2\theta_j\\ \sin^2\theta_j\end{Bmatrix} + \frac{1}{4}P_S\sum_j^M\sum_{l\neq 1}^M S_jS_l\cos\varphi_{jl}\begin{Bmatrix}\cos\theta_j\\ \sin\theta_j\end{Bmatrix}\begin{Bmatrix}\cos\theta_l\\ \sin\theta_l\end{Bmatrix}\sum_k^N c_j^k c_l^{k*}$$

where P_S and P_{LO} are the optical powers of signal and LO respectively, c_j^k is the complex amplitude of the *k*-th spectral chip of the *j*-th code, S_j is the OOK signal (0 or 1) θ_j is the polarization angle of the signal from *j*-th user, $\varphi_{j,LO}$ is the relative phase delay between that user and LO, and φ_{jl} is the relative phase delay of two users. The first term here contains both signal and MAI , while the last term represents speckle or OBI. The detector integrates over one bit interval and thus eliminates most of MAI – and the balanced detection scheme eliminates OBI completely resulting in four photocurrents

$$I_{1-4} \sim \frac{T}{2\sqrt{2}}\sqrt{P_{LO}P_S}S_i\begin{Bmatrix}\cos\varphi_{i,LO}\\ \sin\varphi_{i,LO}\end{Bmatrix}\begin{Bmatrix}\cos\theta_i\\ \sin\theta_i\end{Bmatrix}$$

The standard procedure of squaring and summation then removes phase and polarization ambiguity resulting in the photo-current proportional to $S_j^2=S_i$ (for OOK). One should observe that no phase locking of the lasers is needed and the requirements for the laser linewidth are relaxed (about 1MHz for 10GBs signal rate). Furthermore, in both ring (Fig.1c) and tree LAN one can distribute the pulses of one master oscillator to all users and thus automatically assure the frequency locking of the signal and LO.

3. Modeling

A system of 32 users at 10 Gb/s with 1.0 ps optical pulses at $f_c = 200THz$ was considered. Of the 200 lines in the spectral main lobe, 32 were used for SPC using Hadamard-Walsh [6] sequences of length 32 (Fig.2). The MAI level (in dB) produced by each user, relative to the level of the received signal, is shown in Fig. 3. When all 31 interferers are present, the signal-to-MAI power ratio is 12.7 dB. It has been determined by numeric experimentation that increasing the sequence length by including more lines reduces the MAI, but the reduced amplitudes of the additional lines become problematic with respect to system noise. In fact, the main spectral lobe contains 0.97 of the total energy in the pulse, and the energy between ±0.16 of the zero crossings of the lobe (corresponding to 32 of the 200 spectral lines) contains 0.78 of the total pulse energy.

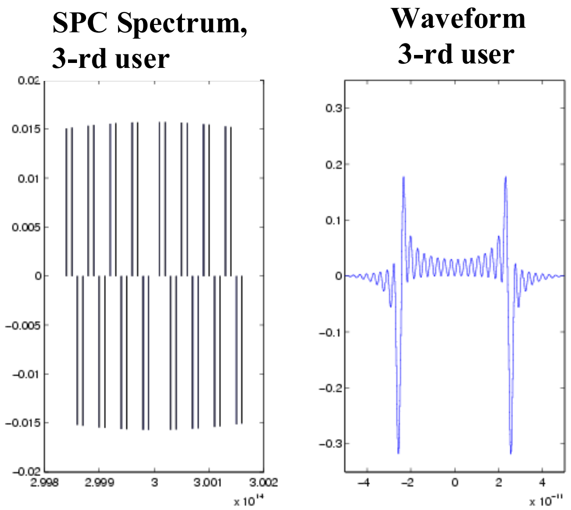


Fig.2 SPC Spectrum and Waveform

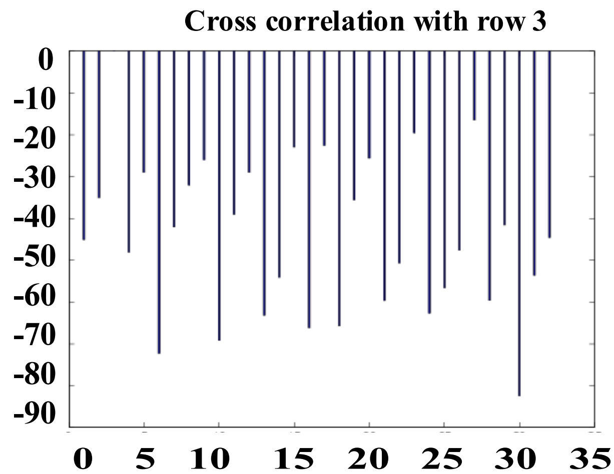


Fig.3 Relative MAI levels (dB)

4. Conclusions

We have proposed and modeled a novel, fully orthogonal OCDM scheme with low MAI and speckle and high spectral efficiency that requires neither nonlinear optical devices nor phase locking. The proposed scheme is most attractive in the local access networks.

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