Non-Uniform Spectral Phase Encoding in Optical CDMA Networks

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Abstract—We propose a novel encoding scheme for spectral phase encoding in optical code-division-multiple-access networks. This method improves the orthogonality of encoded waveforms between multiple users by compensating for the non-ideal spectral shape of the sub-picosecond mode-locked laser pulse source. Simulation results demonstrate improved bit-error-rate (BER) performance. Compared with the traditional uniform encoding scheme, the non-uniform encoding scheme offers five orders of magnitude of BER reduction.

Index Terms—Optical CDMA, Spectral Phase Encoded Time Spreading (SPECTS), Multiple user interference (MUI)

I. INTRODUCTION

Optical code-division-multiple-access (O-CDMA) is an attractive access technology for allowing flexible reconfiguration of high-capacity optical networks [1,2]. Spectral phase encoded time spreading (SPECTS) [1,2] realizes O-CDMA through spectral phase encoding of ultrashort coherent optical pulses. It has shown superior performance compared to incoherent O-CDMA schemes by effectively suppressing multiple-user-interference (MUI) [3], leading to a recent 320 Gb/s O-CDMA network testbed demonstration[4].

In SPECTS O-CDMA, pseudo-random codes are applied to a sub-picosecond optical pulse through phase shifting (coding) its spectral components. Such an operation transforms the impulsive high-intensity sub-picosecond optical pulse into a low-intensity, time-spread noise-like waveform. Within a SPECTS O-CDMA network, each user broadcasts data-modulated phase-encoded optical pulses to all other users through a power splitter (e.g., a star coupler). At the receiver, the decoder can receive information from the intended sender by reversing the corresponding phase shifts, thus recovering the high-intensity ultra-short pulses. On the other hand, the spectral phases of pulses from other senders will not be correctly recovered, and these pulses will persist as low intensity, time-spread multiple-user interference (MUI) [5].

MUI causes detection errors and limits the capacity of an O-CDMA network. Maintaining orthogonality among the encoded waveforms from different users is essential to MUI reduction in SPECTS O-CDMA [3]. Unfortunately, the non-ideal spectral characteristics of practical sub-picosecond laser pulse sources (e.g., a fiber mode-locked laser with pulse compression) make it difficult to achieve true orthogonality. This paper proposes a non-uniform encoding scheme that compensates for the non-ideal spectrum of practical optical sources to enhance the orthogonality of the encoded waveforms among users. A similar non-uniform compensation scheme was first introduced in [6], on spectral amplitude encoded O-CDMA. This paper generalizes the principle to spectral phase encoded O-CDMA, and presents a thorough evaluation of its performance through theoretical analyses, comparison of experimental obtained waveforms, and bit-error-rate (BER) simulations. Our results have demonstrated significant performance gain through this non-uniform encoding scheme.

II. MOTIVATION AND ANALYSIS

The synchronous SPECTS O-CDMA system has been shown to outperform the asynchronous counterpart by providing higher capacity and lower bit error rates [4]. Here we limit our analysis to a synchronous system. For on-off-keyed modulation, the E-field received by the i-th decoder can be written as [7]

\[ e^i(t) = \frac{E_b}{2\pi} \sum_{m=1}^{M} \int_{-\Omega/2}^{\Omega/2} E^m(\omega) e^{j\omega t} d\omega + \frac{1}{2\pi} \sum_{n=0}^{N-1} b^n \sum_{j=1}^{N} \int_{-\Omega/2}^{\Omega/2} E^n(\omega) e^{j\omega t} e^{-j\Omega m} e^{j\omega t} d\omega \]

where \( b^n = \{0,1\} \) is the data bit sent by the m-th encoder; \( \Omega_n \) the upper bound of the n-th frequency component (chip); \( N \) the total number of frequency chips; \( M \) the total number of users; \( E^m(\omega) \) the continuous time Fourier transform (CTFT) of the temporal function of the original ultra-short pulse; and \( C^n(\omega) = e^{-j\phi_n^i} \) the phase code (where \( \phi_n^i \) is the phase shift amount) applied to the n-th frequency chip by the m-th encoder. The first term is the recovered short pulse from the intended sender (the i-th encoder); the second term is the MUI. Minimizing the MUI term is essential in the designing of the O-CDMA system, since the accumulation of MUI leads to detection errors.

Previous theoretical analyses assumed that the sub-picosecond pulse possesses an ideal uniform spectrum or a constant CTFT response (\( E^m(\omega) = E_n \)) [2,8]. Therefore, it is natural to move \( E^m(\omega) \) out of the integration-summation in (1) and, without loss of generality, set the decision point at \( t = 0 \). Thus, the field contribution from the MUI becomes

\[ e_{\text{MUI}}(0) = \frac{E_b}{2\pi} \sum_{m=1}^{M} \int_{-\Omega/2}^{\Omega/2} \sum_{n=0}^{N-1} b^n \sum_{j=1}^{N} C_n^m C_j^i \int_{-\Omega/2}^{\Omega/2} d\omega \]

\[ = \frac{E_b}{2\pi} \sum_{m=1}^{M} \int_{-\Omega/2}^{\Omega/2} \sum_{n=0}^{N-1} b^n \sum_{j=1}^{N} C_n^m C_j^i \int_{-\Omega/2}^{\Omega/2} d\omega \]

where \( \Delta \Omega = \Omega_n - \Omega_{n+1} \) is the uniform frequency chip size. Also, if the code set \( \{C_n^m\} \) is orthogonal, then \( \sum_n C_n^m C_n^i = 0 \) for \( m \neq i \) and the MUI term reduces to zero. This analysis shows...
that under the conditions of ideal uniform spectrum, single point detection and orthogonal code set, one can achieve the elimination of the MUI.

Although it is difficult to perform single point detection at \( t = 0 \) without ultra-fast electronics, a narrow time gate centered at the decision point can approximate its effect [9]. Such gating can preserve all of the energy from a correctly decoded pulse while suppressing most of the energy from the MUI. All simulations in this paper have incorporated such a time gate to suppress the MUI. Furthermore, the orthogonal condition for the phase code can be achieved by the selection of either an orthogonal code set (e.g., Walsh codes) or a quasi-orthogonal code set (e.g., cyclic shifted \( m \)-sequences). However, optical pulses with a uniform spectrum are uncommon in reality. Hence the orthogonality condition eliminating the MUI may no longer hold for pulses with a non-ideal spectrum, leading to performance degradations. Our SPECTS O-CDMA testbed [9] utilizes a fiber compressed mode-locked laser as the ultra-short optical pulse source, and due to non-linearity, the spectrum of its output pulses exhibit features of a complex structure, such as spikes, which cause performance degradation due to the loss of orthogonality.

III. RESULTS: NON-UNIFORM ENCODING SCHEME

In order to improve the performance of SPECTS O-CDMA systems with a non-ideal pulse spectrum [7], we propose a novel non-uniform encoding scheme. In Eq. (1), we observed that, if \( \int_{-\infty}^{\infty} E_l^*(\omega) d\omega = I_0 = \text{constant} \), the MUI term becomes

\[
\varepsilon_{\text{MUI}}(0) = \frac{L_n}{2\pi} \sum_{n=1}^{N_m} b^n \sum_{l=1}^{L} C_{n,l} C_{n,l}^*;
\]

thus the orthogonality condition described in Section II continues to hold.

Since both our simulation and experimental realization of O-CDMA encoding is done in the discrete format in which each frequency chip consists of either a set of points (as in simulations) [7] or a group of pixels (as in experiments) [9], it is convenient to use discrete notation. After an approximation of the integration in Eq. (1), the MUI term can be expressed as

\[
\varepsilon_{\text{MUI}}(0) \approx \frac{1}{2\pi} \sum_{n=1}^{N_m} b^n \sum_{l=1}^{L} C_{n,l} C_{n,l}^* E^*_l \delta\omega,
\]

where \( E^*_l \) is the E-field spectral amplitude of the \( l \)-th point (pixel); \( l_0 \) the upper pixel index of the \( n \)-th frequency chip; and \( \delta\omega \) the frequency pixel width. We approximate the electrical field amplitude in each frequency chip with its average value. Thus, Eq. (4) can be approximated by

\[
\varepsilon_{\text{MUI}}(0) \approx \frac{1}{2\pi} \sum_{n=1}^{N_m} b^n \sum_{l=1}^{L} C_{n,l} C_{n,l}^* E^*_l \delta\omega,
\]

where \( L_n = L_L - L_{l_0} \) is the width in terms of pixels of the \( n \)-th frequency chip. It is clear that, if we choose the width of each frequency chip according to its average E-field amplitude to make \( E^*_n = \text{constant} \), then Eq. (4) can be rewritten as:

\[
\varepsilon_{\text{MUI}}(0) = \frac{1}{2\pi} \text{constant} \times \delta\omega \times \sum_{l=1}^{L} b^n \sum_{l=1}^{L} C_{n,l} C_{n,l}^*.
\]

As analyzed in Section II, the orthogonal condition for \( \{C\} \) leads to \( \sum_{l=1}^{L} C_{n,l} C_{n,l}^* = 0 \) for \( m \neq l \); therefore, the MUI will reduce to approximately zero.

The key to reducing the MUI with the use of this non-uniform encoding scheme is to vary the value of \( L_n \) according to the value of \( E^*_n \), such that \( E^*_n L_n = \text{constant} \), whereas the traditional uniform encoding scheme as shown in Fig. 1 (a) keeps \( L_n \) constant. The full compensation of a complex spectrum often requires a rather complex scheme (\( N \) possible different values of \( L_{l_0} \)) that is hard to implement in practical systems, since \( N \) could be well over 100. A more practical approach should balance between complexity and effective compensation by the selection of a non-uniform encoding method that involves a small number of different values for \( L_{l_0} \). Fig. 1 (b) shows an example of the use of five different levels of \( L_{l_0} \) to make \( E^*_n L_n \) roughly constant. Smaller \( L_{l_0} \) values are chosen for frequency chips with higher amplitudes (the center chips) and larger \( L_{l_0} \) values for those with lower amplitudes (the edge chips), as expected. The horizontal axis is in reference to 193.55 THz optical carrier frequency.

Experimental and simulation results indicate that this new non-uniform encoding scheme, as shown in Fig. 1 (b) indeed improves the performance of a SPECTS O-CDMA system. Fig. 2 shows a qualitative comparison between the uniform and non-uniform schemes by comparison of one MUI waveform resulting from the encoding and decoding of a pulse with 64-bit Walsh code #5 and #53 (as designated by the Hadamard command in Matlab), respectively. One can easily observe that the interference level at the decision point \( (t = 0) \) drops dramatically for the non-uniform case (Fig. 2 (b)). The solid lines are simulated waveforms, and the dashed lines are cross correlation traces obtained from the SPECTS O-CDMA testbed [9]. The simulation results agree well with the experimental
The impact of this non-uniform encoding scheme differs for different interferers, and this case may be one of the best cases in which significant improvement is observed. In order to observe the average effect, our BER simulation studies allow all possible interferers from one code family a fair chance to access the network.

A more quantitative comparison involves the calculation of the detected optical energy of the MUI passing through the time gate. Fig. 3 shows the simulation results of normalized interference as a function of the number of interferers for both uniform and non-uniform encoding schemes and for various time gate durations, all with binary, 31-bit cyclic-shifted $m$-sequence phase codes. Compared to the uniform encoding scheme, the non-uniform scheme reduces interference energy. Simulation results also indicate that such a reduction is more effective for narrower time gating as predicted. For a gating time of 0.3 ps, the non-uniform scheme provides three times greater reduction in interference energy. We have chosen the 0.3 ps optical gate size for our BER simulation in order to demonstrate the impact of this non-uniform encoding scheme. Although difficult, it is possible to achieve a time gate comparable to the ultra-short optical pulse [10].

To further demonstrate the system performance, we compared the BER through simulations. Two code families (cyclic shifted $m$-sequences and Walsh codes) of different lengths were chosen as phase codes. The simulation includes a given number of users, each randomly assigned a phase code within the same orthogonal code set. All users synchronously send random bits through on-off keying in the SPECTS O-CDMA network. A single decoder decodes the combined signals from all users. The signal from each user contains random phase and polarization perturbations.

Fig. 4 shows the BER results for both the uniform and the non-uniform encoding schemes, applying the aforementioned two code families of length 63/64 (Fig. 4(a)) and 127/128 (Fig. 4(b)), respectively. For a fair comparison, the only difference between the uniform and non-uniform encoding simulations lies in the division of the pulse spectrum (shown in Fig. 1); all other conditions remain the same. Both code lengths show an overall BER reduction given the same number of users when the non-uniform encoding scheme is applied. For the maximum number of allowed users (the maximum number of codes in each code set), the BER reduction extends to five orders of magnitude (in the case of 128-bit Walsh code, the BER drops from 4e-2 to 2e-7 for 120 users). This result demonstrates that the non-uniform encoding scheme indeed improves the orthogonality between the interfering waveforms from the two code families.

REFERENCES