Non-uniform spectral encoding of measured mode-locked laser pulses for performance enhancement of optical CDMA networks

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Abstract: We propose a novel non-uniform spectral encoding scheme in a SPECTS O-CDMA system. Simulations incorporating measured mode-locked laser pulse spectrum indicate that enhanced BER performance and 8-fold increase in system capacity are possible.

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1. Introduction

Spectra Phase EnCode d Time Spreading (SPECTS) is an optical code-division-multiple-access (O-CDMA) technology which accommodates multiple simultaneous users in an all-optical access network by assigning a unique optical phase code to each user [1]. SPECTS implements the encoding and decoding through all-optical pulse shaping of an ultra-short optical pulse. One of its major attractions is the capability to effectively suppress multi-user interference (MUI) and accommodate large number of users. Experimental demonstration of 16 simultaneous users in a SPECTS OCDMA test bed is being reported [2]. In fact, the orthogonality among all encoded optical pulses from different users is the key to reduce the MUI in a SPECTS system [3]. However, because of typically non-flat spectra of realistic ultra-short optical pulse sources (e.g. a mode-locked laser), true orthogonality among users is often not possible. Our previous work showed that non-uniform phase encoding can improve bit-error-rate (BER) performance for Gaussian pulses [4]. In this paper, we apply similar non-uniform encoding technique to real mode-locked laser pulses with more complex spectral structure. Without non-uniform encoding, such a non-flat spectrum leads to worse BER performance and limits the system capacity. Application of the non-uniform encoding technique allows up to 8-fold improvement in the SPECTS O-CDMA system capacity.

2. Theory

For simplicity, we express the electrical field of the ultra-short pulse in time domain using its discrete samples \( e_k = e(t_k) \), which can be written as the IFFT of \( N \) frequency components:

\[
\epsilon_k = \frac{1}{N} \sum_{n=0}^{N-1} E_n \exp\left[j \frac{2\pi kn}{N}\right].
\]

Here \( E_n \) is the discrete Fourier transform of \( e_k \).

SPECTS O-CDMA achieves optical encoding by applying a phase change to each of the frequency bin component, which is called a “chip”, and the total number (\( N \)) of the “chips” is the length of the phase code. The encoded signal of the \( m \)-th user is then

\[
\epsilon^m_k = \frac{1}{N} \sum_{n=0}^{N-1} E_n \exp\left[j \frac{2\pi nk}{N} + \phi^m_n\right]
\]

where \( \phi^m_n \) is the phase code applied at the \( n \)-th “chip” of the \( m \)-th user. When a binary phase code is applied, \( \phi^m_n \) is set to be either 0 or \( \pi \). The \( i \)-th decoder applies the inverse of the \( i \)-th phase code to the encoded pulse, resulting in the decoded signal as:

\[
\epsilon^{m,i}_k = \frac{1}{N} \sum_{n=0}^{N-1} E_n \exp\left[j \frac{2\pi nk}{N} + \phi^m_n - \phi^i_n\right]
\]

where \( \phi^i_n \) is the spectral phase code applied by the \( i \)-th decoder at the \( n \)-th “chip”. Noted that if \( m = i \), (4) reduces to (1). Therefore, the decoder reconstructs a high-intensity ultra-short pulse from the \( i \)-th encoder. Otherwise the decoder outputs a time spread low-intensity noise-like signal whose shape is determined by \( \phi^m_n - \phi^i_n \).
When $M$ users are sending information simultaneously over the SPECTS O-CDMA network, each user will encode the information with its own encoder and broadcast it through a star coupler. The combined signal is then sent to the decoder. The time domain expression of the decoded pulse at the $i$-th decoder can be expressed as:

\[
\varepsilon'_i = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} E^n_m \exp \left[ \frac{j2\pi nk}{N} + \phi^n_m - \phi^n_i \right],
\]

\[
= \frac{1}{N} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} \left[ E^n_m \exp[j(\phi^n_m - \phi^n_i)]\right]\exp(j\frac{2\pi nk}{N}),
\]

\[
= \frac{1}{N} \sum_{n=0}^{N-1} \left[ \sum_{m=0}^{N-1} (E^n_m C^n_i) \right]\exp(j\frac{2\pi nk}{N}),
\]

where $C^n_i = e^{j\phi^n_i}$ is the phase code applied at the $n$-th “chip”.

From (5), if $E^n_m = \text{constant} = E_0$ for all $l$ and $m$, we can move it out of the summation to yield:

\[
\varepsilon'_i = \frac{E_0}{N} \sum_{n=0}^{N-1} \left[ \sum_{m=0}^{N-1} (C^n_m C^n_i^*) \right]\exp(j\frac{2\pi nk}{N}).
\]

If the phase code $C$ is limited to a complete orthogonal set, then $\sum_n C^n_m C^n_i^* = N$ for $m = i$ and $\sum_n C^n_m C^n_i^* = 0$ for $m \neq i$. Therefore it maximizes the response for the desired user (encoder and decoder apply conjugate phase code) and suppresses the interference from other undesired users. Several previous studies are based on this flat spectrum assumption, predicting very optimistic performance of the SPECTS O-CDMA [3, 5].

Unfortunately, pulses with such flat spectrum are rare in practice. Any deviation from such an ideal condition will lead to the loss of the orthogonality, which compromises the decoder’s ability to suppress MUI. Simulation results show that even pulses with Gaussian spectral shape will result in BER performance far worse than ideal predictions based on flat spectral shape [4]. In [4], we proposed a novel scheme to improve the system performance by dividing the pulse spectrum into frequency “chips” with varying bandwidth, instead of dividing it uniformly with the same bandwidth for each “chip” as traditionally done in SPECTS OCDMA. The bandwidth of each “chip” is determined by its spectral intensity, with smaller bandwidths for “chips” of higher spectral intensity and larger bandwidths for “chips” of lower spectral intensity. The purpose of this non-uniform division is to equalize the power within each “chip”. Earlier results showed that by simply dividing the Gaussian spectrum into “chips” with three different bandwidths, we could accommodate twice as many users for a given BER.

3. Simulation result for the practical mode-locked laser pulse

![Simulation result for the practical mode-locked laser pulse](image)

The realistic optical pulses are not Gaussian. Our SPECTS O-CDMA test-bed utilizes ultra-short pulses generated by a fiber mode-locked laser [6]. As Fig. 1(a) and (b) indicate, such a laser has a non-flat spectral shape due to the non-linearity in the fiber. Compared with the hypothetical system with a Gaussian spectral shape, the real system with such a pulse spectrum performs even worse due to the degraded orthogonality. To improve the capacity of such a system, we apply our novel non-uniform encoding and decoding method to this measured pulse shape. Since the spectral shape of the mode-locked laser pulse in Fig 1 (a) is much more complex than a Gaussian pulse, the simple 3-level encoding scheme applied to the Gaussian pulses becomes insufficient for spectral compensation. On the other hand, the non-uniform encoding scheme should not be too complicated to implement in real systems. We
have to search for a compromising non-uniform encoding that is sufficient enough to compensate the spectrum yet simple enough to implement. We divide the pulse spectrum into 7 classes with five different “chip” bandwidths. The “chip” bandwidth is chosen so that the integrated power within each “chip” is approximately the same. Fig. 2 shows an example of dividing the spectrum for a 31-bit code (a) uniformly (b) non-uniformly and the resulting average integrated power within each chip for (c) uniformly encoding case and (d) non-uniformly encoding case.

![Fig. 2. Demonstration of the pulse spectrum division for (a) uniform and (b) non-uniform case. Spectral intensity (dashed line) and integrated power within each “chip” (solid line) for (c) uniform encoding and (d) non-uniform decoding. (e) BER as a function of number of interferers for uniform and non-uniform encoding scenarios, phase codes applied are 31, 63 and 127 bits cyclically shifted m-sequence.](image)

We chose cyclically shifted m-sequence of length 31, 63 and 127 as phase codes for BER simulations. These codes are quasi-orthogonal, which means that they have little MUI given ideal pulse. Our simulation incorporates a non-linear optical time gate to differentiate the correct decoded signal and incorrectly decoded signal and to eliminate MUI as described in [7]. The simulated scenario is that a certain number of random users (each assigned with a phase code chosen from the same set of the m-sequence) can simultaneously send either bit ‘1’ or ‘0’ through the SPECTS O-CDMA system to a single decoder (desired user). Each user has random phase delays and polarization directions relative to the desired user.

Fig. 2 (e) is the simulated BER performance of a SPECTS OCDMA with mode-locked laser pulse for both the uniform and non-uniform encoding schemes. The total spectral bandwidth is identical for both cases. The simulation result shows that the non-uniform encoding scheme reduces the BER values of the SPECTS O-CDMA by more than 3 orders of magnitude for a given number of users. For code lengths of 31, 63, and 127, the network capacity taken at BER less than 1E-7 increases from 5 to 19, 7 to 37, and 11 to 91 simultaneous users, respectively.

4. Conclusion

In this paper, we demonstrate ways of applying the non-uniform encoding/decoding scheme for an SPECTS OCDMA system relying on fiber mode-locked laser pulses. Simulations of the non-uniform phase coding indicate significant improvements in terms of spectral efficiency by accommodating up to eight times as many users in the OCDMA network compared with uniform phase encoding for a given BER performance in the network.

5. References


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