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Design and simulations of a spectral efficient optical code division multiple access scheme using alternated energy differentiation and single-user soft-decision demodulation

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a new approach to optical Code Division Multiple Access (CDMA) network transmission scheme using alternated amplitude sequences and energy differentiation at the transmitters to allow concurrent and secure transmission of several signals. The proposed system uses error control encoding and soft-decision demodulation to reduce the multi-user interference at the receivers. The design of the proposed alternated amplitude sequences, the OCDMA energy modulators and the soft decision, single-user demodulators are also presented. Simulation results show that the proposed scheme allows achieving spectral efficiencies higher than several reported results for optical CDMA and much higher than the Gaussian CDMA capacity limit.

1. Introduction

Privacy of information is one of the main features of optical Code Division Multiple Access (OCDMA) when compared to Wavelength Division Multiple Access (WDMA), Time Division Multiple Access (TDMA), Orthogonal Frequency Division Multiple Access (OFDMA) or random access schemes. In addition, optical CDMA offers several other features, such as flexibility of asynchronous and decentralized networking and total bandwidth utilization by all network users [1–21]. However, practical OCDMA schemes have been relying on single user detection/ decoding due to implementation complexity constraints and signal processing speed requirements in optical networks. Consequently, the achieved spectral efficiencies have been low due to severe multi-user interference that degrades transmitted information, as illustrated in Table 1 for selected OCDMA transmissions [5–9]. Moreover, for most of the considered two-dimensional (time/wavelength) OCDMA spreading sequences, the normalized achievable spectral efficiencies are shown to be between 0.1 and 0.5 bits per channel use [10]. These achieved low spectral efficiencies have limited the deployment of OCDMA systems.

One of the most frequently considered theoretical capacity analysis of CDMA with single-user decoding is based on the corresponding chip-level Gaussian multi-access channel with Gaussian signaling and Gaussian multi-user interference ([8]). Using Shannon's (single-user) Gaussian channel capacity result, the (cumulative) throughput limit for a K-user network is given by:

$$C = \frac{K}{2}log_2\left(1+\frac{P}{\sigma^2+(K-1)P}\right) \overset{K\to\infty}{\to} 0.72 \;\; bits/chip, \tag{1}$$

where P is the power limit of the individual power-controlled users and σ^2 is the noise variance. This paper presents a new approach that offers the inherent information privacy of OCDMA and achieves very high spectral efficiencies. In the proposed approach, no spreading is used at the transmitters, but each signal is differentiated by its energy prior to being sent. Energy differentiation has also been explored in [22], where power optimization is considered, for concurrent multi-level phase shifted keying (MPSK) signals, using a multiuser detector based on successive interference cancellation. As opposed to [22], this paper considers *error control coding* and *amplitudes alternation* at the transmitters, *on-off keying* (OOK) modulation for optical channels and *single-user, soft-decision demodulation* at the receivers. In addition, this paper proposes the design of both the alternated amplitude sequences used at the transmitters to allow energy differentiation and the single-user, soft-decision demodulation used at the receivers. Although experimentation and implementation are not the focus of this paper, practical considerations are discussed for implementing the proposed techniques.

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Table 1
Selected OCDMA spectral efficiencies.

Reference	Number of users (K)	Spreading length (N_s)	Error control code rate (r_c)	Modulation rate (r_m)	Spectral efficiency $\eta = (K \times r_c \times r_m)/N_s$ bits/channel use
[5]	30	32×32	1	1	0.029
[6]	500	23×435	1	1	0.050
[7]	50	300	1	1	0.153
[9]	470	318	0.465	2	1.374
This paper	10	1	0.4922	1	4.922

2. System and channel models

2.1. Proposed transmission scheme

Fig. 1 illustrates the schematic block diagram of the proposed optical network transmission with K synchronous users transmitting data simultaneously and independently (e.g., without co-operation). K independent and identically distributed (i.i.d.) binary information packets of length L, composed of equiprobable symbols 0 and 1, are encoded using a given error control code (e.g. Reed Solomon and/or turbo code) of rate r_c. Each encoded packet is consequently sent through user-specific data interleaver, which randomly permutes the coded data sequence, in order to distribute more evenly the codewords in the packets. This random permutation enables better data recovery and noise resistance at the receiver by removing memory from the encoded data packets. It also increases the system security and privacy of information, since only the desired receiver has knowledge of the permutation order.

The interleaved data sequences are next fed into the proposed OCDMA modulators, which multiply the encoded and interleaved input sequences, by users' alternated amplitude sequences of the same length. This step allows users' energies differentiation at each time instant. As a result of this modulation technique, symbols from different users have different energies at any given time instant. Finally electrical to optical conversion is performed and on-off keying is used to transmit data through the optical channel. At the receiver, optical to electrical conversion is first performed and the initial data order is recovered by the deinterleavers. Finally, single-user soft decision demodulation and decoding is performed.

2.2. System's components

This section describes in more detail the functionalities of the main modules of the proposed OCDMA transmission, e.g., the error control encoder, the interleaver and the OCDMA modulator.

2.2.1. Error control encoders

The first block in the proposed system is the error control encoder. The role of the error control encoder is to add redundancy in the users' information prior to being transmitted. This redundancy provides time diversity and increased robustness (against noise) to the transmitted information. The proposed system is compatible with various error control encoders. However, the performance of the system depends on the used error control codes. Simulation results in Section 7 use Reed-Solomon and/or turbo encoders and decoders due to their ability to achieve near-capacity throughput [23,24].

2.2.2. Interleavers

The role of the interleaver is twofold. First, it permutes the coded data sequence, in order to scramble and distribute more evenly the encoded data in the packet. The overall objective is to reduce the memory created from the mapping of the (uncoded) bits into codewords (by adding redundancy) by the error control encoder. As results, consecutive bits in an encoded data sequence may be differently affected by the noise. For instance, if a deep noise event affects consecutive bits, those bits are not in their initial order and original data may be recovered from the others (redundant) bits of the codeword. The second objective of the interleaver, perhaps the most important in this design, is to allow increased privacy since the interleaving order is specific to a given user and known only to its corresponding receiver. On the other hand, the deinterleaver, used at the receiver, uses the knowledge of the permutation order to recover the initial data order. In this paper, random interleaving is considered for simplicity.

2.2.3. OCDMA modulators

The OCDMA modulators multiply the encoded and interleaved input sequences, by users' alternated amplitude sequences of the same length. This step is used to achieve users' energies differentiation at each time instant. Next, the modulators generate electrical signals that are proportional to the OCDMA modulated sequences, which are finally converted into light intensity using the E/O converters. The uniqueness of the proposed OCDMA demodulators' lies in the use of alternated amplitude sequences to differentiate users' transmit powers. Consequently, the design of the amplitude sequences are described in detail in Section 3.

2.3. Channel model

K users are assumed to transmit data simultaneously, synchronously and independently over the optical channel. During modulation, transmission and demodulation processes, optical signals are assumed to add up without beatings and direct detection is performed at the receivers. Moreover, this paper considers the case of an optical transmission with enough number of transmitted photons, where the dominant noise affecting the

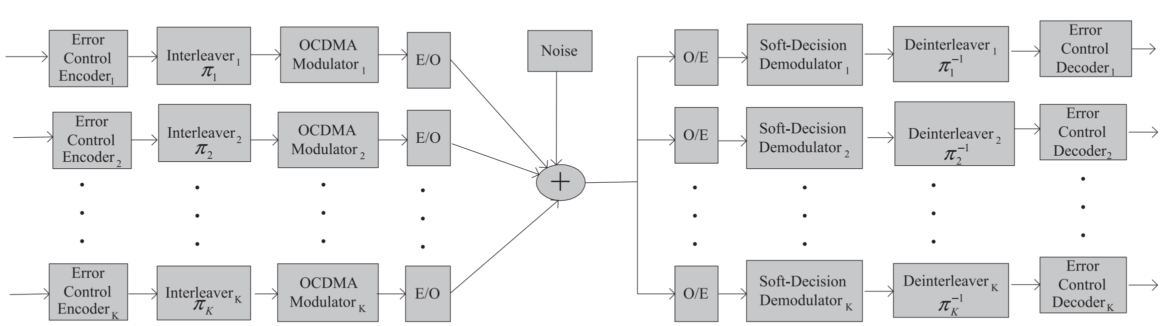

Fig. 1. Schematic block diagram of the proposed optical CDMA network transmission/reception schemes. (E/O & O/E are electrical to optical and optical to electrical signals' converters).