Optical MC-CDMA System for IM/DD based Optical Wireless Communications

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Summary

The optical waves and radio waves, both follow same laws of Physics. However wavelength of optical waves is much smaller as compared to radio waves. There is exponential growth in the demand for data access, but the RF spectrum is already congested. Optical Wireless Communication (OWC) emerges as an alternative solution for today's high-speed data communication. Optical Orthogonal Frequency Division Multiplexing (O-OFDM) with intensity modulation and direct detection (IM/DD) is a modulation scheme commonly used in OWC systems. There are two common families of O-OFDM signal structures mostly used in OWC systems. First one is bipolar Gaussian signal called DC-biased optical OFDM (DCO-OFDM) and the second is unipolar half Gaussian signal called asymmetrically clipped optical OFDM (ACO-OFDM). In this paper a novel modulation scheme based on O-OFDM and code division multiple access (CDMA) is proposed. The new technique enables the implementation of simple and spectrally efficient OWC system. The proposed scheme support simultaneous transmission of multi-user data. Simulation results illustrate that Optical-MC-CDMA provides an excellent performance complexity trade-off.

Key words:

Optical Wireless Communication, Optical MC-CDMA, Optical OFDM, Visible Light Communication

1. Introduction

During the last few years, the deployment of wireless communication systems has increased rapidly. With the advent of sensitive network applications like real-time gaming, telepresence, telesurgery, HD video streaming, video conferencing and cloud services occupy a major portion of today's network bandwidth. The bandwidth demand of these applications could result in the congestion of network. The bandwidth available in ISM band is very limited and cannot cater to the needs of high throughput and low latency applications.

Scientist have been exploring the higher end of the spectrum for wired optical transmission for extremely large throughput and high performance data transmission; however, more recently the focus has shifted to Optical Wireless transmission system.

The optical spectrum is much larger than the RF spectrum, as it covers up to 790 THz. Fundamentally, visible light communication (VLC) can be classified into two categories; Free Space Optics (FSO) for outdoor and Optical Wireless Communication (OWC) for short range or indoor communication.

For outdoor environment, it can be used as a point to point link between the buildings. The transmission distance for FSO may be of the order of few kilometers. It can also be used for spacecraft communication in the upper space [1].

Since optical region of frequency spectrum is unregulated, it can be used free of cost worldwide. Another important benefit of OWC is that optical luminaries widely installed in indoor setups, therefore installation of OWC would save infrastructure as well as operational costs.

Numerous research organizations are actively involved in standardization of VLC e.g. VLC Consortium in Japan. The OMEGA project of European Union and D-Light project at University of Edinburgh have demonstrated functional prototypes on VLC. IEEE 802.15.7 VLC task group issued a standard for VLC in 2011. It defines the physical layer for short range VLC. More recently, development of Light Fidility (LiFi) protocol is under study [2]. This protocol aims to develop a complete networking framework for full-duplex all optical transmission system for indoor applications. This protocol promises to provide throughput to the tune of hundreds of Giga bits per second.

Modulation schemes play a very crucial role in design of robust yet low complexity transmission system. Development of modulation scheme for OWC has been a topic of intense research over the past decade; Several single and multi-carrier schemes have been proposed in literature. A comprehensive review of OWC schemes is available in [3,4,5]. Multi-carrier transmission systems have several advantages over conventional single-carrier systems namely robustness in multi-path environment, simple channel equalization with a simple transmit and receive structure. It is for these reasons, we concern ourselves with multi-carrier modulation techniques. The first multi-carrier OWC system was reported in [6]. In OWC the message is transmitted through intensity modulation and direct detection i.e. IM/DD, therefore the

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modulated signals must be real and unipolar. Since the data modulated on subcarriers is complex and bipolar. The modulated data must be Hermitian symmetric. This significantly limits the efficiency of the OFDM based OWC modulation schemes as only half of the carriers carry information. There exist several variants of OFDM based OWC schemes such as DC-biased optical OFDM (DCO-OFDM) proposed in [6,7], and asymmetrically clipped optical OFDM (ACO-OFDM) [8]. Some other modulation schemes based on O-OFDM have also been reported in the literature recently, for example FLIP-OFDM [9], ASCO-OFDM [10] and Polar OFDM [11]. All of the above variants of O-OFDM format the data to be Hermitian symmetric. This incurs 50% and 75% loss of spectral efficiency in the case of DCO and ACO respectively. However, all of the above schemes are either bandwidth and/or energy inefficient and/or require computational overhead.

In [12] Fakidis etal have implemented optical CMDA scheme with multiple users with M-ary PAM data.

In this paper, we propose a novel optical modulation scheme called Optical-MC-CDMA. MC-CDMA was originally proposed in [13], for exhaustive review please refer [14]. Our proposed system does not require OFDM symbols to be Hermitian symmetric. In this paper, we have combined Polar OFDM [10] with CDMA to enhance the throughput of the system. The CDMA does not only enable multiple access to different users as in the case of wireless networks. In this case CDMA also serves the purpose of spreading and despreading the real and imaginary parts of complex waveform. In CDMA system spreading may be performed either in time domain or frequency domain. In the proposed system, spreading is performed in time domain. To the best of our knowledge no such attempt is available in literature.

The organization of paper is as follows: Section 2 outlines the system model and proposed modulation scheme. Section 3 presents the simulation parameters and discusses performance results. Section 4 concludes this paper.

Notation: small bold alphabets $\boldsymbol{x}$ represent vector while capital bold alphabets X represent matrix, $\odot$ is the Kronecker product operator.

2. System Model

MC-CDMA system is based on OFDM frame work. However, MC-CDMA technique combines best features of CDMA and OFDM. Some of the appealing features include higher throughput, simple transmitter/receiver module and better error performance. The combination of OFDM and CDMA is promising candidate for future optical networks. As briefly discussed in the previous section that CDMA uses orthogonal codes for multiplexing and demultiplexing of data from different users. There exist several orthogonal sequences in literature such as PN, Gold, Walsh and Walsh Hadamard (WH) Codes. Only WH codes have been considered here.

2.1 Transmitter Model

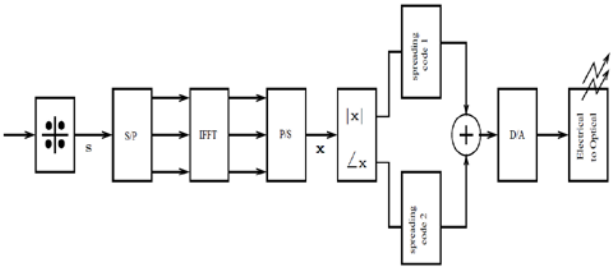

Fig. 1 Block Diagram of Proposed Transmitter Model

Fig. 1 illustrates the block diagram of transmitter model. The input of the system is a block of $N \times 1$ data symbols mapped from any complex modulation scheme, and converted into parallel format.

$$\boldsymbol{s} = [s(0), s(1), \cdots, s(N-1)]^T. \tag{1}$$

Inverse Fast Fourier transform (IFFT) operation is applied to the input stream **s**, to obtain a time domain output signal **x**

$$\boldsymbol{x}(\boldsymbol{k}) = \frac{1}{N}\sum_{n=0}^{N-1} s(n) e^{\frac{j2\pi nk}{N}} \tag{2}$$

where n , k = 0, 1, 2, ..., N − 1 is the sample index in frequency and time domain respectively. These data samples are complex in nature so they contain real and imaginary components just like RF OFDM. The magnitude and phase information of the signal can be described as

$$\boldsymbol{x} = |\boldsymbol{x}| e^{j\boldsymbol{\theta}} \tag{3}$$

Now these complex samples are separated into N amplitude and N phase samples.

$$|\boldsymbol{x}| = \boldsymbol{r} \tag{4}$$

$$\arg(\boldsymbol{x}) = \boldsymbol{\theta} \tag{5}$$

Now we have two parallel streams r(k) and θ(k) of subcarriers. Since r(k) is the magnitude of the waveform, it will always be positive; the value of θ(k) lies between 0 to 360o. The minimum value of θ is mapped to 0 and its maximum value is mapped to 1. Now CDMA technique is applied on each magnitude and phase sample. Here two separate spreading codes C1 and C2 are used to spread r(k) and θ(k). The length of each spreading code is 'L' which is equal to number of chips per bit.

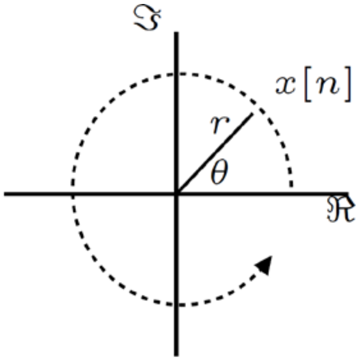

Fig. 2. Operation of Cartesian to Polar Coordinate Conversion

In this work WH codes are considered for spreading sequence. The resulting signals are defined:

$$\gamma_r = \frac{1}{\sqrt{L}}(C^1 \odot I_N)x_r \tag{6}$$

$$\gamma_i = \frac{1}{\sqrt{L}}(C^2 \odot I_N)x_\theta \tag{7}$$

where, C1 and C2 are spreading codes, L is the length of spreading code and $\mathbf{I}_N$ is the identity matrix of N X N. Finally, both the signals are combined together to yield

$$\boldsymbol{r} = \boldsymbol{r}_r + \boldsymbol{r}_i \tag{8}$$

The resulting signal is converted into analog form and finally electrical/optical conversion takes place before the transmission.

2.2 Receiver model

The transmitted optical signal passes through wireless channel. Generally, there are two modes for optical wireless link for indoor optical wireless systems, Line of Sight (LOS) and diffused. In this work only LOS model is considered. Therefore, the appropriate model for noise will be Additive White Gaussian Noise (AWGN). The front-end of receiver is a photo-diode which converts optical signal into electrical. The block diagram of receiver is shown in Fig. 3. Now the received signal (after opto/electrical-conversion and baud rate conversion) can be written as

Table 1: Simulation Parameters

Parameters	4-QAM	16-QAM	64-QAM
N Subcarrier	32	32	32
N Sample Size	256	256	256
N_{symb}	20	20	20
N_{sim}	50000	50000	50000

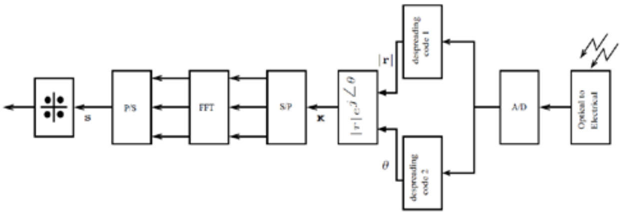

Fig. 3 Block diagram of proposed receiver model

$$\boldsymbol{y} = \boldsymbol{r} + \boldsymbol{n} \tag{9}$$

where $\mathbf{y}$ is $N_1 \times 1$ received vector, $\mathbf{n}$ is AWGN. After analog to digital conversion the received signal is fed into CDMA decoder. Since our signal comprises of two parts; magnitude and phase so the decoder consists of two parallel paths. After de-spreading the received magnitude and phase signals can be written as:

$$\hat{\boldsymbol{r}}_r = \left(\boldsymbol{I}_N \odot C^{1^T}\right)\boldsymbol{y} \tag{10}$$

$$\hat{\boldsymbol{r}}_i = \left(\boldsymbol{I}_N \odot C^{2^T}\right)\boldsymbol{y} \tag{11}$$

The two signals are input to polar to Cartesian operation and the combined complex-valued signal is

$$\hat{\boldsymbol{r}} = \hat{\boldsymbol{r}}_r e^{j\hat{\boldsymbol{r}}_i}. \tag{12}$$

After serial to parallel conversion the resultant samples are fed into OFDM decoder module

$$\hat{s}(n) = \sum_{k=0}^{N-1} \hat{r}(k) e^{-j\frac{2\pi nk}{N}}, \tag{13}$$

where $\hat{s}(n)$ is the hard decoded outcome of the receiver . This work extends the idea further to consider simultaneous transmission of multiple-users. The data of multiple users can be decomposed using (4) and (5), then spread using (6) and (7) using a set of orthogonal sequences and then ultimately combined as in (8). The samples may be recovered through (10) and (11) using appropriate sequences. This may enhance the overall bandwidth efficiency of the system at the expanse of BER performance due to the MAI. In the following section we present simulation performance of proposed scheme in single and multi-user scenarios.

3. Simulation Model and Results

This section discusses the simulation result of Optical Polar MC-CDMA scheme. The receiver front-end shot noise and thermal noise are modeled as AWGN random variable $n\sim\mathcal{CN}(0,\sigma_n^2)$. Line of sight configuration is considered, thus no cyclic prefix (CP) is assumed, $N_{CP} = 0$.

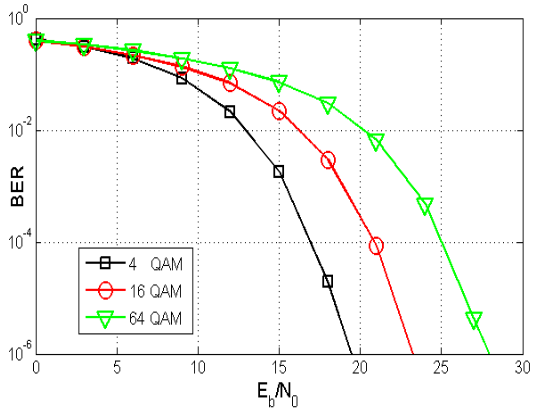

Fig. 4. BER performance of Optical MC-CDMA system for one and three user system in the presence of AWGN noise with 4/16/64 QAM constellations. 1000,000 OFDM symbols, with WH spreading sequence (L=8).

The bit error rate (BER) quantifies bit error performance as a function of signal to noise ratio (SNR). The limit of simulated electrical SNR is up-to 30 dB. This limit matches with the reported measure SNR for typical indoor optical wireless communication system.

A burst of data consists of 20 OFDM symbols with M-QAM constellation. WH code of size 8 is used for spreading data signal. If number of subcarrier is 32 then the dimension of modulated symbol is 256. For a fair comparison the energy of spreading sequences is normalized.

Fig. 4. illustrates the BER performance for M-QAM symbols (with M=4,16 and 64) assuming a single user case. The key parameters of simulations are described in table I.

Fig. 4. illustrates the performance for 4/16/64 QAM modulation in a single user case. Fig. 4 illustrates that for a reference BER of 10^{-4}, 4 QAM requires 17 dB where are 16 and 64 QAM require 21 and 25 dB respectively.

Fig 5. illustrates the BER performance of proposed scheme in the case of one, two and three users. It is evident that there is a marginal performance loss due to MAI. The comparison of all the three BER curves, we have chosen BER of 10^{-4} as a reference point. 16-QAM transmission for single user case required 21 dB while two and three users case require 24 and 26 dB respectively. This is very useful feature of Optical MC-CDMA system which allows significant rate enhancement. MC-CDMA combines the best features of OFDM such as simple implementation and channel equalization with CDMA, which offers straight forward multi-user access.

It is apparent from Fig. 4 and 5 that the BER performance of proposed optical-MC-CDMA system is poor at low SNR region; However at the moderate and high SNR BER performance improves significantly. This is intuitive as distortion of modulated waveform will have significant impact on all subcarriers. As pointed out in [15] that illumination in a typical indoor environment delivers SNR in excess of 60 dB.

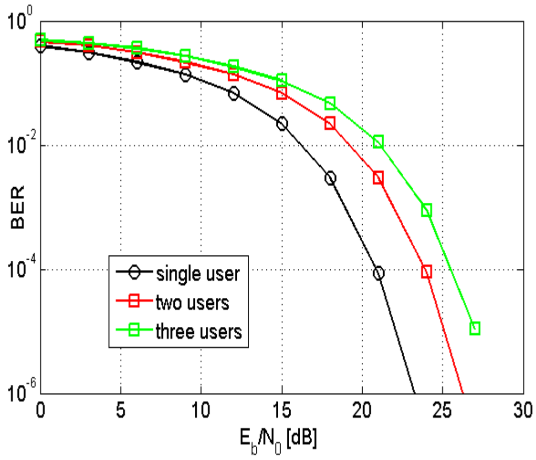

Fig.5BER performance of Optical MC-CDMA system for one, two and three user system in the presence of AWGN noise with 16 QAM constellations. 1000,000 OFDM symbols (each user), with WH spreading sequences (length L=8).

In the next subsection we compare the performance of proposed and contemporary modulation techniques. Three parameters have been chosen for the comparison i.e. spectral efficiency, energy efficiency, and implementation complexity.

3.1 Spectral Efficiency

In DCO-OFDM scheme half of the subcarriers are redundant to ensure Hermitian symmetry and obtain real-valued signal. In ACO-OFDM half of the spectrum remains unutilized while only a quarter of subcarriers transmit meaningful data and the remaining subcarriers are Hermitian symmetric. Therefore the waveform is real-valued. Hence the spectral efficiency of ACO OFDM is one fourth as compare to typical RF OFDM system. For DCO system the spectral efficiency is approximately twice as compared to ACO. In our proposed system, we utilize both real and imaginary parts of data i.e. Hermitian Symmetry is not required as well as there is no clipping of negative part of signal. If the size of IFFT is N then the comparison of spectral efficiencies can be given as:

Table 2: Comparison of Spectral Efficiency

Modulation Scheme	ACO OFDM	DCO OFDM	Proposed Scheme
Spectral Efficiency	$(\frac{(N/4)-1}{N}).\log_2 M$	$(\frac{(N/2)-1}{N}).\log_2 M$	$\frac{N_U}{L}\log_2 M$

Where N_U is the number of independent users; the above results show that the spectral efficiency of our proposed scheme is better than the other conventional schemes. It is approximately twice as compared to DCO OFDM and 4 times as compare to ACO OFDM. This increase in efficiency is at the cost of higher bandwidth. As we know that in case of OWC THz of bandwidth is available free of cost. So in our proposed scheme a higher data rate will be achieved because of spreading of data in two separate symbols and transmitting it simultaneously.

3.4 Energy efficiency

In ACO-OFDM all even indexed carrier remain unutilized while odd index carriers have conjugate symmetry i.e. $s(n) = -s(n + \frac{N}{2}), 0 \leq n \leq \frac{N}{2}$. Since, only half of the odd subcarriers carry the useful information and the other half of odd sub-carriers are redundant.

In DCO OFDM, signal quality depends upon the DC biasing. If high DC biased is applied, then alot of power is consumed in biasing and less amount of power in useful signal. This consequently degrades the system performance. Conversely if lower biased is used the performance of system deteriorates due to clipping of negative waveform. Thus renders DCO-OFDM infeasible for higher order QAM. In our proposed scheme, all of the subcarriers carry useful information and does not require any biasing. The spreading sequences are normalized, therefore it is more energy efficient as compared to others.

3.5 Computational Complexity

Fast Fourier transform (FFT) algorithm is used in OFDM to perform modulation and demodulation operation. The number of real operations required by the FFT of size N is of the order of $N\log_2(N)$.

ACO-OFDM and DCO-OFDM schemes require one Fourier transformation each at transmitter and receiver therefore proposed Optical-MC-CDMA scheme has a comparable implementation complexity and computational overhead.

3.6 Comparison of proposed model with non-conventional variants

Four non-conventional variants of Optical OFDM are considered here. First three variants ADO-OFDM, Flip OFDM and Layered ACO-OFDM required Hermitian symmetry, hence are suboptimal choice in terms of spectral efficiency, and computational overhead due to additional pre and post processing in transmitter and receiver. In polar OFDM magnitude and phase part of data concatenated before transmission therefore throughput efficiency is half compared to the proposed scheme. The advantage of our proposed scheme comes at the cost of higher bandwidth. By multiplexing data from multiple users the throughput can be enhanced even further. But bandwidth is not a problem, because THz of free bandwidth is available in the optical spectrum. Finally, we conclude that our proposed modulation scheme performs better than the non-conventional variants discussed in this paper.

4. Conclusion and Future Work

This paper presents a modulation technique that combines OFDM with CDMA to enhance the system throughput of OWC systems. We have presented a brief review of existing OWC modulation techniques to highlight their limitations. Unlike the variants of optical OFDM system available in the literature, the proposed system enhances the efficiency by transmitting complex bipolar data symbols and relaxing the symmetry requirements. The CDMA scheme allows simultaneous transmission of data from multiple users at full data rate. The proposed scheme is energy efficient as it does not require any biasing or clipping of the modulated signal. The proposed system does require considerably higher bandwidth; however as already discussed in the introduction OWC systems have abundant (free) spectrum available at their disposal.

As a future work, it would be of great interest to consider other (more realistic) channel models and diffused light sources as described in [5]. It will also of great interest to explore the effects of diversity techniques on overall performance of the proposed system. This is specially relevant as multiple luminaries are available in typical indoor setup.

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