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Demonstration of high-speed multi-user multi-carrier CDMA visible light communication

Chao Yang, Yuanquan Wang, Yiguang Wang, Xingxing Huang, Nan Chi *

Key Laboratory for Information Science of Electromagnetic Waves (MoE), Department of Communication Science and Engineering, Fudan University, 220 Handan Road, Shanghai 200433, China

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ABSTRACT

We experimentally demonstrated a high-speed multi-user multi-carrier code-division multiple access (MC-CDMA) visible light communication (VLC) system. By employing a commercially available red light emitting diode (LED) and an avalanche photo diode (APD), we achieved a 16-user VLC system enabled by MC-CDMA, pre- and post-equalization, with an overall bit rate of 750 Mb/s over 1.5 m free-space transmission. The measured bit error ratio (BER) of each user is below the 7% pre-forward-error-correction (pre-FEC) threshold of 3.8×10^{-3}.

1. Introduction

Recently, there has been an increasing interest in light emitting diode (LED) -based visible light communication (VLC), which is considered a promising candidate in wireless optical communication [1–3]. Simultaneous illumination and communication, larger bandwidth, absence of electromagnetic interference and security to eyes make it an alternative to typical radio frequency (RF) technique. Besides, the low cost and wide spread of LED lays a solid foundation for the application of VLC as an access scheme in indoor and outdoor scenarios.

In the presented works, one of the main applications of VLC is to build a broadcast network serving for different users simultaneously in some indoor scenarios. A series of multiplexing access approaches are applied in VLC system, such as code division multiple access (CDMA) [4–6], orthogonal frequency division multiplexing (OFDM) [7], polarization division multiplexing (PDM) [8] and sub-carrier multiplexing (SCM) [9]. In [4], some simulations based on model designing and numerical calculation are proposed in CDMA-VLC system with no experimental demonstration. In [5,6], an experimental optical CDMA-VLC system is proposed based on random orthogonal codes (ROC). However, the adopted ROC code is not an orthogonal code with suboptimal correlation property, which decreases the spectrum efficiency severely. Due to the limited modulation bandwidth of LED in VLC system, the overall bit rate in [5] is limited to less than 1 Mb/s, which is not suitable for high-speed wireless transmission. Besides, in [7], typical OFDM is adopted in VLC system for high spectral efficiency and robustness against multipath effect. But OFDM scheme only make use of frequency diversity and is very sensitive to frequency offset like Doppler shift, which damages the orthogonality of each subcarrier.

In this paper, we proposed and experimentally demonstrated a high-speed VLC system based on multi-user multi-carrier CDMA (MC-CDMA) scheme [10]. MC-CDMA scheme is the concatenation of CDMA and OFDM, which allows the proposed system benefit from several advantages of both multi-carrier modulation and spread spectrum technology by offering, for instance, high flexibility, high spectral efficiency, simple and robust detection techniques and narrow band interference rejection capability. Besides, Walsh–Hadamard codes are adopted instead of ROC, which are absolutely orthogonal and increase the multiplexing efficiency. Signals generated by different users are 64-ary quadrature amplitude modulation (64QAM) mapped before combined and modulated to MC-CDMA signal. Moreover, pre- and post-equalization are employed for attenuation compensation and data recovery, respectively. By employing these techniques, a 16-user MC-CDMA VLC system with an overall bit rate of 750 Mb/s is demonstrated after 1.5 m free-air transmission. The measured bit error ratio (BER) of each user is below the 7% pre-forward-error-correction (pre-FEC) threshold of 3.8×10^{-3}.

* Corresponding author.
E-mail address: nanchi@fudan.edu.cn (N. Chi).

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2. Principle

The basic MC-CDMA is generated by a serial concatenation of classical direct spread CDMA (DS-CDMA) and OFDM. As a CDMA scheme, different users share the same bandwidth at the same time adopting orthogonal spreading codes. At the receiver, the data of each user is separated by applying different user specific spreading codes, which means the separation of signals is carried out in the code domain. Moreover, multi-carrier modulation is realized by using the low-complex OFDM operation to reduce the symbol rate and the amount of inter-symbol interference (ISI) per sub-channel. This ISI reduction is significant in spread spectrum systems where high chip rates occur.

MC-CDMA transmits a data symbol of one user simultaneously on several narrowband sub-channels. These sub-channels are multiplied by the chips of the user-specific spreading code, as illustrated in Fig. 1. The spreading code adopted in our demonstration is Walsh–Hadamard code by the spreading factor of 16. Orthogonal Walsh–Hadamard codes are simple to generate recursively by using Hadamard matrix generation shown in (1). The maximum number of available orthogonal spreading codes is L which determines the maximum number of active user.

$$C_L = \begin{bmatrix} C_{L/2} & C_{L/2} \\ C_{L/2} & -C_{L/2} \end{bmatrix}, \quad \forall\, L = 2^m,\, m \geq 1,\, C_1 = 1. \tag{1}$$

MC-CDMA offers a flexible system design, since the spreading code length does not have to be chosen equal to the number of sub-carriers, allowing adjustable receiver complexities.

3. Experimental setup

Fig. 2 illustrates the block diagram of the proposed MC-CDMA VLC system. In this demonstration, different services data from multiple users are first mapped into 64QAM signals and multiplied by orthogonal Walsh code respectively. Then, the data from different users are added and modulated as a multiplexed MC-CDMA signal. Before the modulation process, pre-equalization based on 1-tap zero-forcing algorithm is involved to compensate the low-pass feature of light emitting diode (LED). The pre-equalization is power redistribution in principle, which is realized by software (MATLAB) before the signal is launched into AWG. The process does not bring any noise enhancements into the system. After adding cyclic prefix (CP), up-sampled by a factor of 4, the signal is filtered by a rectangular filter with the aid of MATLAB, then the baseband MC-CDMA signal consists of 128 subcarriers is up-converted to a center frequency of 70.3125 MHz. After up-conversion, the occupied bandwidth is from 7.8125 MHz to 132.8125 MHz, which avoids the low-frequency distortion of LED.

The generation of the aforementioned MC-CDMA signal is processed using MATLAB software, and then loaded into an arbitrary waveform generator (AWG, Tektronix 710) for digital-to-analog conversion (DAC). The sample rate of AWG is 500MSa/s and the chip rate is 750 Mb/s. After being filtered by a low-pass filter (LPF) and amplified by an electrical amplifier (EA), the MC-CDMA signal is modulated onto the visible lightwave adopting a bias tee with direct current (DC) bias. The LPF with 3-dB bandwidth of 150 MHz is employed to filter out the high-frequency noise. A commercial available red LED (Cree, PLCC) generating a luminous flux of about 6 lm is employed as the transmitter. The 3-dB bandwidth of LED is 20 MHz, which can be increased to 150 MHz by utilizing aforementioned pre-equalization. The LED is driven by a voltage source at room temperature (25 °C). Then the lightwave is transmitted via atmosphere and concentrated by a lens, finally detected by an avalanche photodiode (Hamamatsu APD, 0.5 A/W sensitivity at 800 nm and gain = 1) in the receiver side. The received MC-CDMA signal is sampled in a rate of 1GSa/s using a high-speed oscilloscope (OSC, Agilent 54855A) and processed by offline MATLAB DSP programs.

In offline DSP, the received signal is down-converted to baseband. The baseband time-domain MC-CDMA signal is transformed to frequency domain with fast Fourier transmission after serial-to-parallel (S/P) conversion and CP removing. Besides, post-equalization algorithms are employed for channel estimation and data recovery, such as phase offset recovery. To split the data of different user, the equalized digital signal is divided into blocks in the size of 16 chips and multiplied by the Walsh–Hadamard codes used in AWG. Then the BER of each user can be calculated separately after 64QAM de-mapping.

4. Experimental results and discussion

To guarantee the LED works at the linear region, we measured the BERs versus the input power and the bias voltage of LED as shown in Fig. 3. The bias voltage of red LED is varied from 2.1 V to 2.5 V with a step of 0.1 V. As Fig. 3(a) shows, the optimal working point is 2.3 V. The constellation at 2.3 V is much clear than at 2.5 V. Besides, the BER performance versus the input power of red LED is shown in Fig. 3(b), the optimal input power is 12 dB m.

In Fig. 4, we measured the BER performance of all the 16 users after 1 m free-space transmission with and without pre-equalization. The bias voltages and input power of red LED are adjusted at their optimum points as measured above. As shown is Fig. 4, the BERs of all users are below the FEC threshold of 3.8×10^{-3} with pre-equalization, which means that MC-CDMA is practicable as a multiple access scheme of VLC system. However, the BERs are far above FEC threshold without pre-equalization. To explore the effect of pre-equalization, we measured the electrical spectrum of origin signal and received signal after 1 m atmosphere transmission, which is shown in Fig. 5. As Fig. 5(c) shows, the attenuation of the highest frequency is about 30 dB larger than the lowest frequency without pre-equalization, which aggravates the BER performance of all users severely. As a solution, we calculated the channel response based on the spectrum of original signal (Fig. 5(a)) and received signal (Fig. 5(c)), which can be represented by $|H|$. Then the frequency spectrum of original signal

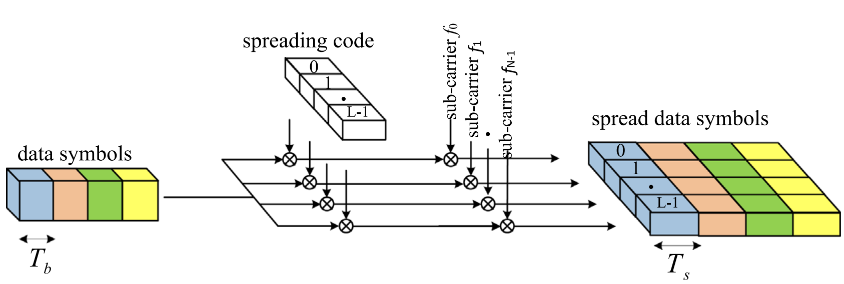

Fig. 1. MC-CDMA signal generation for one user.