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Experimental Demonstration of SCMA for Visible Light Communications

Bangjiang Lin,[1], Xuan Tang,[1],* Zhenlei Zhou,[1] Chun Lin,[1] Zabih Ghassemlooy[2]*

[1]Quanzhou Institute of Equipment Manufacturing, Haixi Institutes, Chinese Academy of Sciences, China
[2] Optical Communications Research Group, Faculty of Engineering and Environment, Northumbria University, U.K.
**Corresponding author: linbangjiang@163.com; xtang@fjirsm.ac.cn*

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We propose an experimental demonstration of sparse code multiple access (SCMA) based visible light communications (VLC) system, in which the multi-dimensional codewords selected from a predefined codebook set are used to encode the transmitted data and a message passing algorithm (MPA) based multi-user receiver is used to detect the multiplexed codewords. Compared with the orthogonal frequency-division multiple access scheme, the SCMA scheme offers 150% overloading gain in the number of supported users at the cost of slightly decreased transmission performance.

Key words: *visible light communications (VLC), sparse code multiple access (SCMA), orthogonal frequency-division multiple access (OFDMA)*

1. INTRODUCTION

Demands for data-intensive applications in next-generation wireless systems have driven visible light communications (VLC) as a promising solution for future indoor/outdoor wireless access networks [1-2]. The main challenges for VLC systems for delivering high-speed connectivity in a relatively large environment are the limited light emitting diode (LED) bandwidth, blocking, free space loss and mobility [2]. LED can be mainly categorized as phosphor-based LED and red-green-blue (RGB) LED. The phosphor-based LED has lower modulation bandwidth compared with RGB LED. However, the lower cost of phosphor-based LED makes it the most widely used in many VLC systems. To address the bandwidth problem, a number of options including high-level modulation, high-speed micro-LEDs, advanced detection techniques, and pre- and post-equalization schemes have been investigated with resounding success [3-4]. Data rates of higher than 10 Gbps using a vertical-cavity surface-emitting laser has been reported in [5]. Additionally advanced modulation schemes such as orthogonal frequency division multiplexing (OFDM), single carrier frequency domain equalization (SCFDE) and orthogonal frequency division multiplexing/offset quadrature amplitude modulation (OFDM/OQAM) [6-10] as well as multiband carrierless amplitude and phase modulation (*m*-CAP) technique [11] have been widely reported.

In this paper, we employ the sparse code multiple access (SCMA) scheme to enhance the bandwidth efficiency of a phosphor-based LED VLC system. SCMA is a special type of non-orthogonal multiple access (NOMA) technique, where a multi-dimensional codebook is used to encode the transmitted binary data in the transmitter (Tx) and the multiplexed codewords are detected by the message passing algorithm (MPA) based multi-user receiver (Rx) with maximum likelihood (ML)-like performance in the Rx. SCMA can transmit the amount of data more than the resource block called overloading and the transmitted codeword should be sparse to mitigate the user interference . In [12], a low complex codebook has been designed for SCMA-VLC, but without experiment verification. We first time experimentally verify the feasibility of SCMA-VLC. The experimental results show that SCMA offers an overloading rate of 150%. Compared with the orthogonal frequency-division multiple access (OFDMA) scheme, SCMA can support more users and offer higher data rate at the cost of slightly decreased propagation distance.

The rest of the paper is organized as follows. In section 2, we introduce the SCMA scheme for VLC systems. Section 3 presents the experiment setup and results for SCMA-VLC followed by the concluding remarks in Section 4.

2. SCMA-VLC SCHEME

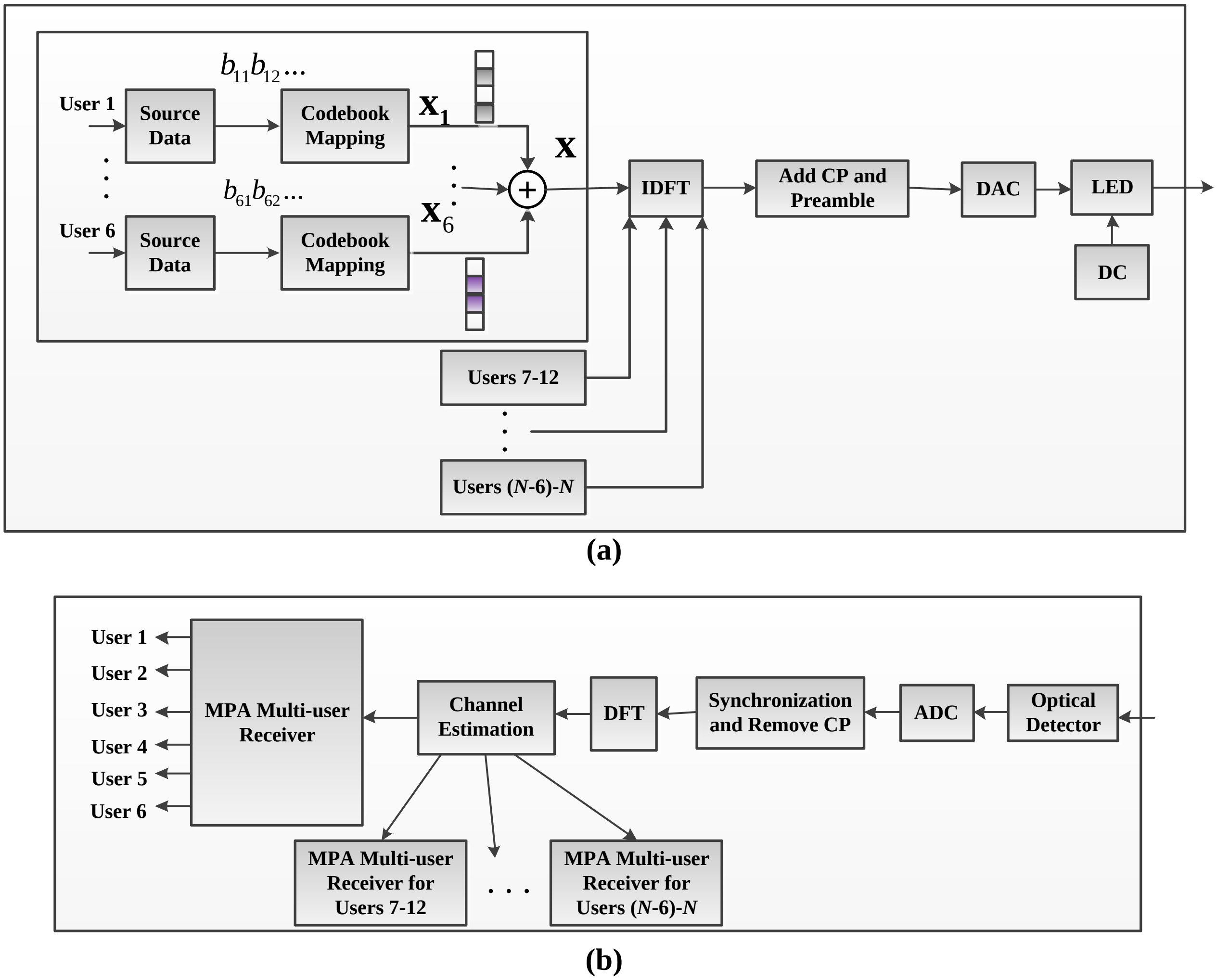

Fig. 1. Block diagram of (a) Tx and (b) Rx for SCMA-VLC (DAC: digital-to-analog converter, ADC: analog-to-digital converter, DC: direct current, DFT: discrete Fourier transform, IDFT: inverse discrete Fourier transform, CP: cyclic prefix)

Fig. 1 shows the schematic block diagram of the proposed SCMA-VLC system with N users. At the Tx, each user is allocated with a dedicated codebook $\mathbf{X}_i$, which is a multi-dimensional constellation vector. The binary bits for each user b_{ij} (j=1, 2) are directly mapped to SCMA codewords. As shown in Fig. 1 (a), the generated codewords from each 6 users are combined firstly (i.e., $\mathbf{X}$) and then fed into the inverse discrete Fourier transform (IDFT) module, in which the transmitted data of the six users are spread over four OFDM subcarriers (SCs 1-4). Each SC carries multiple modulation symbols from different users. The connection between the users and SCs can be represented with a factor graph as shown by Fig. 2. As shown in Fig. 2, on each SC, symbols from 3 users are overlapped with each other, this achieve an overloading rate of 150%. E.g., on SC1, symbols from users 2, 3, and 5 are overlapped with each other. The data of users 7-12 are encoded and spread over SCs 5-8. And the data of other users are encoded using the similar method. After the IDFT operation, cyclic prefix (CP) and preamble are added in each OFDM symbol and in the front of each frame, respectively. They are used to combat the inter-symbol interference (ISI) and to perform channel estimation, respectively. The generated digital OFDM signal is converted to electrical signal via a digital-to-analog converter (DAC), the output of which is direct current (DC) level shifted prior to intensity modulation (IM) of a LED. After free space transmission, a photodiode is used to detect the optical signal. The detected signal is amplified and then converted into digital format by an analog-to-digital converter (ADC). The digital signal is firstly passed through a frame synchronization module. After removing the CP, the signal is transformed into the frequency domain by a discrete Fourier transform (DFT) module and the received signal on the k^{th} SC (k =1, 2, 3, 4) can be expressed as:

$$Y_k = \sum_{j=1}^{6} H_k X_{k,j} + n_k, \tag{1}$$

where H_k denotes the channel response of the k^{th} SC, and n_k is the additive white Gaussian noise. $\mathbf{X}_\mathrm{j} = [X_{1,j}, X_{2,j}, X_{3,j}, X_{4,j}]^T$ is the transmitted codeword of the user j. The channel coefficients **H** can be calculated based on the preamble. Given the received signal **Y,** the maximum posterior probability (MAP) based detection is given as:

$$\hat{\mathbf{X}} = \arg \max_{\mathbf{X} \in \chi_1 \times \chi_2 \times \chi_3 \times \chi_4 \times \chi_5 \times \chi_6} p(\mathbf{X} \mid \mathbf{Y}), \quad \textbf{(2)}$$

in which we consider all the possible transmitted codeword combinations. The number of all the combinations is 4^6. In order to reduce the complexity, the MPA method is considered here in which the belief associated to the edges in the factor graph by passing the extrinsic information of constellation points between user nodes and SC nodes [13-14]. The complexity of the MPA is $M\times4^3$, where M is the number of iterations. The detail workflow for MPA based receiver can be found in [12-13]. By decoding the received signal carried on SCs 5-8, the data of users 7-12 can be recovered from the MPA receiver as shown in Fig. 1 (b) and the data of other users can be removed using the similar method.

3. EXPERIMENT SETUP AND RESULTS

The experimental setup for SCMA-VLC is shown in Fig. 3. At the Tx, the generated modulation symbols from 6 users are superposed together and spread over 4 SCs. The total user number and the number of employed SCs are 6 and 4, respectively. The sizes of DFT and CP are 10 and 0, respectively. Hermitian symmetry is applied for the purpose of generating a real value OFDM signal. The generated SCMA signal is uploaded onto an arbitrary waveform generator (AWG), the output of which is DC-level shifted prior to IM of a commercially available phosphorescent white LED. At the Rx, the optical signal is detected by a commercial photodetector (THORLABS PDA36A), the output of which is amplified and applied to a DAC. The digital signal is captured using a real-time digital oscilloscope for offline signal processing in the Matlab domain in order to recover the transmitted data. All the key system parameters are provided in Table I. The codebooks used in the experiment for the six users are shown as follows:

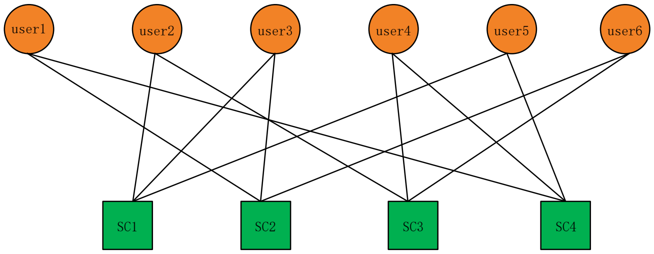

Fig. 2. The factor graph for SCMA with 6 users and 4 resource nodes.

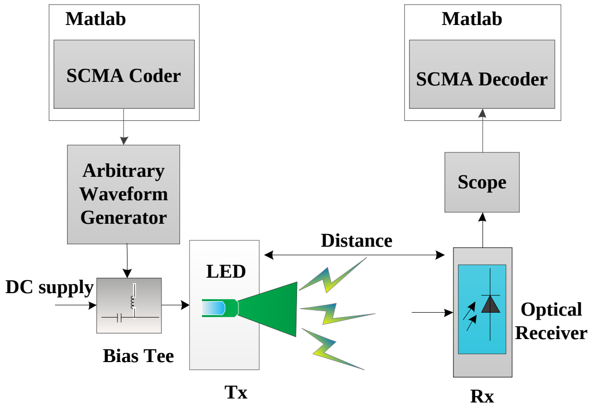

Fig. 3. Experiment setup of SCMA-VLC.

$$C_1 = \begin{bmatrix} 0,0,0,0; \\ -0.1815-0.1318i,-0.6351-0.4615i, \\ 0.6351+0.4615i,0.1815+0.1318i; \\ 0,0,0,0; \\ 0.7851,-0.2243,0.2243,-0.7851 \end{bmatrix}, \quad \textbf{(3)}$$

$$C_2 = \begin{bmatrix} 0.7851,-0.2243,0.2243,-0.7851; \\ 0,0,0,0; \\ -0.1815-0.1318i,-0.6351-0.4615i, \\ 0.6351+0.4615i,0.1815+0.1318i; \\ 0,0,0,0 \end{bmatrix}, \quad \textbf{(4)}$$

$$C_3 = \begin{bmatrix} -0.6351+0.4615i,0.1815-0.1318i, \\ -0.1815+0.1318i,0.6351-0.4615i; \\ 0.1392-0.1759i,0.4873-0.6156i, \\ -0.4873+0.6156i,-0.1392+0.1759i; \\ 0,0,0,0; \\ 0,0,0,0 \end{bmatrix}, \quad \textbf{(5)}$$

$$C_4 = \begin{bmatrix} 0,0,0,0; \\ 0,0,0,0; \\ 0.7851,-0.2243,0.2243,-0.7851; \\ -0.0055-0.2242i,-0.0193-0.7848i, \\ 0.0193+0.7848i,0.0055+0.2242i \end{bmatrix}, \quad \textbf{(6)}$$

$$C_5 = \begin{bmatrix} -0.0055-0.2242i,-0.0193-0.7848i, \\ 0.0193+0.7848i,0.0055+0.2242i; \\ 0,0,0,0; \\ 0,0,0,0; \\ -0.6351+0.4615i,0.1815-0.1318i, \\ -0.1815+0.1318i,0.6351-0.4615i \end{bmatrix}, \quad \textbf{(7)}$$

$$C_6 = \begin{bmatrix} 0,0,0,0; \\ 0.7851,-0.2243,0.2243,-0.7851 \\ 0.1392-0.1759i,0.4873-0.6156i, \\ -0.4873+0.6156i,-0.1392+0.1759i; \\ 0,0,0,0 \end{bmatrix}. \quad \textbf{(8)}$$

TABLE I. System parameters

Parameter	Value
LED	
- Bandwidth	~ 5 MHz
- Semi-angle of half power	~ 60°
- Transmit power	~180 mw
PIN photodetector	
- Active area	13 mm^2
- Responsivity	< 0.44A/W
- Bandwidth	10 MHz
- Field of view	~90 °
SCMA modulation	
- DFT	10
- CP	0
- User number	6
- Employed SCs	4
- Bitrate per user	2 Mb/s
OFDM modulation	
- DFT	10
- CP	0
- User number	4
- Employed SCs	4
- Bits per symbol	2
- Bitrate per user	2 Mb/s

Fig. 4 shows the actual experiment setup for SCMA-VLC. The *P-I* characteristics of the LED is shown in figure 5, where the most linear part is within the current range of 200 – 1400 mA. Fig. 6 shows the average bit error rate (BER) as a function of transmission distance for a range of iteration and a sampling rate of 10 MS/s for AWG. Note that, the BER performance improves with the increasing number of iterations. The optimum iteration is 4 beyond which there is no further improvement. The total bit rate achieved R_{bT} = 10 M×4/10×150%×2 = 12 Mb/s. Compared with OFDMA scheme, SCMA can support more users. Table II shows the relationship between the received optical power and the distance shown in Fig. 6. Note that the received optical power is measured by a power meter, which has different active area from the photo detector used in the experiment.

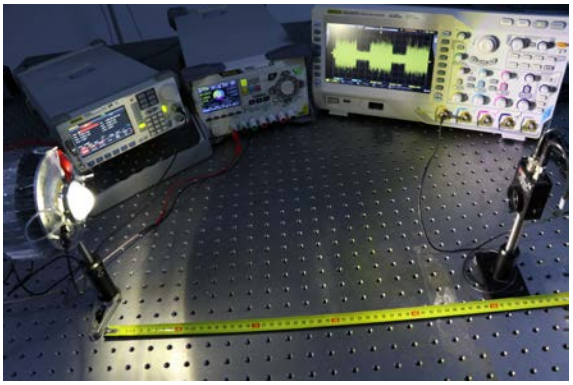

Fig. 4. Photograph of the actual experiment setup

TABLE II. The relationship between received power and distance

Received optical power (dBm)	Distance (cm)
1.36	32
0.13	38
-1.12	44
-2.24	51
-3.34	59
-4.06	65

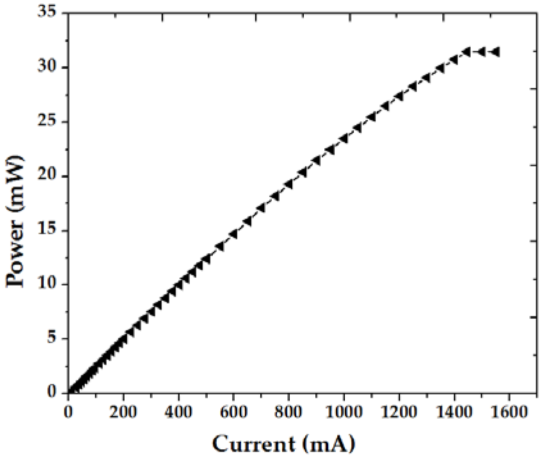

Fig. 5. Output optical power as a function of current for the LED.

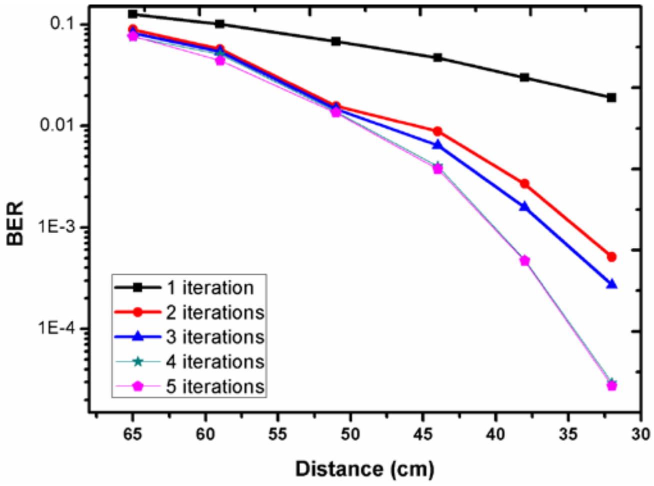

Fig. 6. Average BER performance for a range of iteration.

Fig. 7 depicts the BER performance as a function of propagation distance for both OFDMA and SCMA schemes. Each BER is calculated from the average of all the users. For OFDMA with quadrature phase shift keying (QPSK), the total number of SCs used is 4 and each SC is allocated to a specific user. The DFT and CP sizes are 10 and 0, respectively. The total bit rate for OFDMA is 8 Mb/s. Compared with OFDMA, SCMA achieves higher data rate while using the same number of SCs at the cost of slightly decreased transmission distance. As shown in Fig. 7, the obtainable transmission distances at a BER of 1e-3 are about 43 and 40 cm for OFDMA and SCMA, respectively. This is because the SCMA requires more signal to noise ratio (SNR) to achieve a given BER. Note that the BER performance of SCMA can be further improved by a better codebook for each user to achieve a large shaping gain. The lens is not used to calculate the BER in Figs. 6 and 7. With a lens being in front of the receiver, the transmission distance can be further increased.

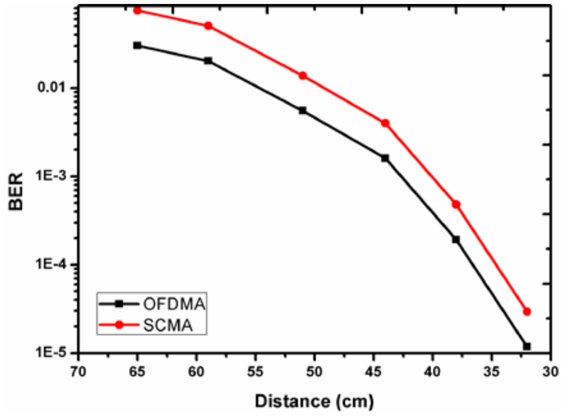

Fig. 7. Average BER performance against propagation distance for OFDMA and SCMA.

4. CONCLUSIONS

In this paper, we first time experimentally demonstrated a SCMA based VLC system, in which the transmitted binary bit stream was directly mapped onto multi-dimensional codewords and a MPA based multi-user receiver was used to detect the multiplexed codewords. SCMA offered higher system capacity compared with OFDMA.

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