

# Performance Evaluation of OFDM with Multi-mode Index Modulation in Bandlimited Low-pass VLC Systems

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**Abstract.**—In this paper, the performance of orthogonal frequency division multiplexing (OFDM) with multi-mode index modulation (MMIM) in bandlimited low-pass (LP) visible light communication (VLC) systems is evaluated. Specifically, we investigate and compare two techniques for LP effect mitigation, i.e., discrete Fourier transform (DFT) spreading and subblock interleaving. It is shown by the simulation results that DFT spreading outperforms subblock interleaving in terms of bit error rate (BER), but subblock interleaving can enable multi-user communication via orthogonal subblock division multiple access.

**Keywords**—visible light communication; orthogonal frequency division multiplexing; multi-mode index modulation (key words)

## I. INTRODUCTION

In recent years, visible light communication (VLC) has been considered as a promising technology for the sixth generation (6G) communication systems, as VLC systems have abundant spectrum resources, which are also low-cost, highly secure and do not generate electromagnetic interference [1]. Since VLC systems using commercially available LEDs are generally bandlimited which have a

low-pass (LP) frequency response, various techniques have already been reported in literature to enhance the overall performance of VLC over LP channels, such as multiple-input multiple-output (MIMO) [2-6], orthogonal frequency division multiplexing (OFDM) [7-10], and so on. Specifically, OFDM has been shown to be an efficient technique to improve the data rate of bandlimited LP-VLC systems.

Lately, OFDM with index modulation has been further adopted in VLC systems, including single-mode index modulation (SMIM), quadrature single-mode index modulation (QSMIM) and dual-mode index modulation (DMIM) [11-13]. Nevertheless, OFDM with multi-mode index modulation (MMIM) has not yet been considered in bandlimited LP-VLC systems. Moreover, in order to overall the LP effect, both discrete Fourier transform (DFT) spreading and subblock interleaving have been reported [8,13], but the performance comparison between these two techniques has not yet been studied.

In this paper, we focus on the performance evaluation of OFDM with MMIM in bandlimited LP-VLC systems through computer simulations, where DFT spreading and subblock interleaving are studied and compared.

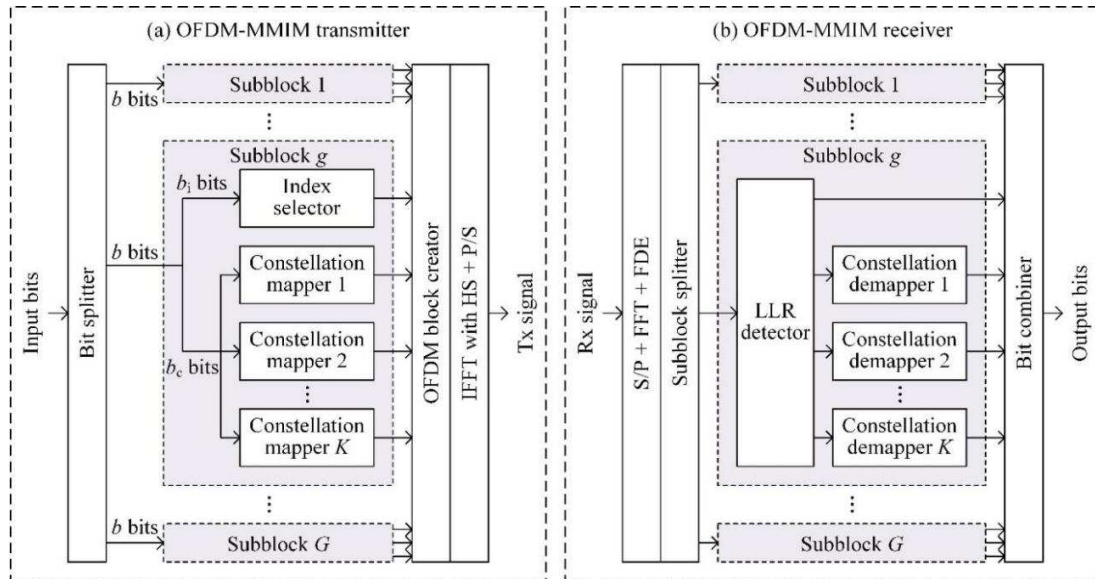


Figure 1. Block diagram of OFDM-MMIM.

## II. SYSTEM MODEL

The model of VLC systems using OFDM-MMIM is introduced in this section, where the principle of OFDM-MMIM is first described, and DFT spreading and subblock interleaving are further discussed.

### A. Principle of OFDM-MMIM for VLC

Fig. 1 illustrate the block diagram of OFDM-MMIM. Here, the input bits are split into  $G$  streams and each stream is sent into a subblock. Within each subblock, the input  $b$  bits are further split into  $b_i$  and  $b_c$  bits, where  $b_i$  bits are used to perform index selection while the  $b_c$  bits are used to perform constellation mapping accordingly. Assuming the subblock size is  $N=4$  and each subcarrier transmitting a distinctive constellation symbol (i.e.,  $k=1$  and  $K=N$ ), the corresponding MMIM mapping table is shown in Table I. After OFDM block creation, the inverse fast Fourier transform (IFFT) which is imposed with the Hermitian symmetry (HS) constraint and the parallel-to-serial (P/S) conversion are further executed to obtain the real-valued and non-negative transmitted signal, which will drive the LED to emit optical signal for transmission.

TABLE I. MMIM MAPPING TABLE FOR  $N=4$  AND  $K=1$ .

Index bits	Index of $M_1$	Index of $M_2$	Index of $M_3$	Index of $M_4$	Subblock
00	1	2	3	4	$[S_1, S_2, S_3, S_4]$
01	2	3	1	4	$[S_2, S_3, S_1, S_4]$
11	1	4	2	3	$[S_1, S_4, S_2, S_3]$
10	3	4	1	2	$[S_3, S_4, S_1, S_2]$

At the receiver side, the received signal captured by a photo-detector (PD) undergoes the serial-to-parallel (S/P) conversion, forward fast Fourier transform (FFT) and frequency-domain equalization (FDE). Subsequently, a log-likelihood ratio (LLR) detector is utilized for signal recovery, and hence the output bits can be finally obtained via a bit combiner [14].

The performance of OFDM-MMIM largely depends on the adopted multi-mode constellation design. Fig. 2 shows three multi-mode constellation designs considered in the following investigations, which are based on the three different 8-ary constellations, i.e., 8-ary quadrature amplitude modulation (8-QAM), 8-ary phase-shift keying (8-PSK), and circular (7,1)-QAM [13].

### B. DFT spreading for LP mitigation

For the purpose to reduce peak-to-average power ratio (PAPR) and overcome the LP effect simultaneously, DFT spreading has been widely applied in VLC system using OFDM with index modulation [12,13]. As per Fig. 1, DFT spreading can be performed after OFDM block creation.

The basic idea of DFT spreading is to convert the multi-carrier signal into a quasi-single-carrier signal. For OFDM and OFDM with index modulation, multi-user communication can be easily enabled through orthogonal frequency division multiple access (OFDMA) and orthogonal subblock division multiple access (OSDMA), respectively [15]. However, it is difficult for the obtained signal after executing DFT spreading to support multi-user communication.

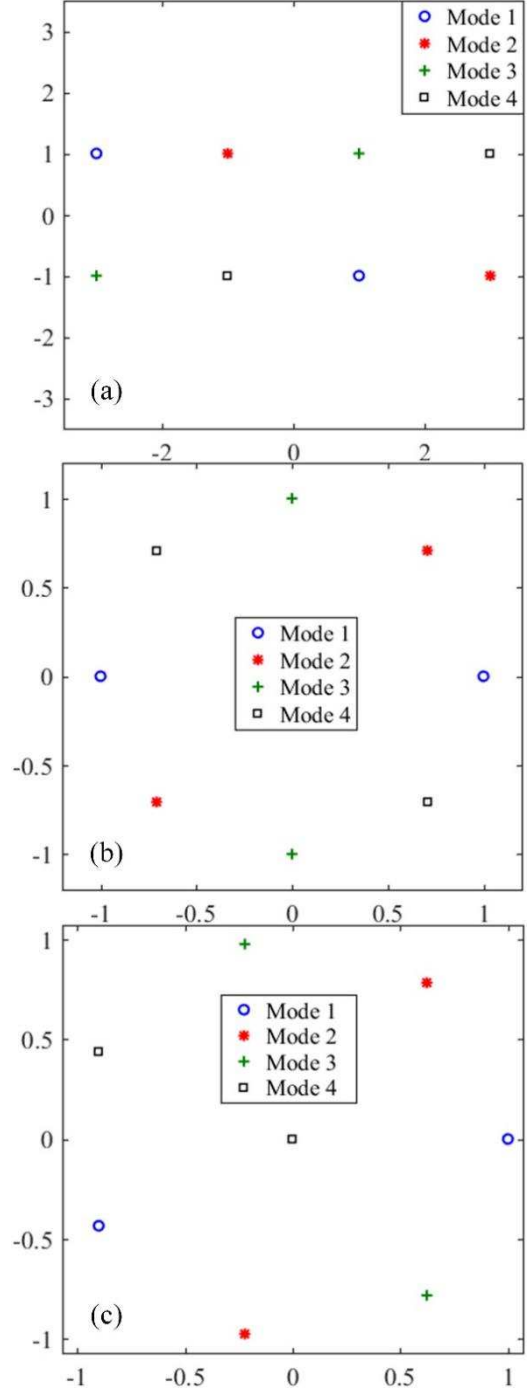


Figure 2. Multi-mode constellation design based on (a) 8-QAM, (b) 8-PSK and (c) circular (7,1)-QAM.

### C. Subblock interleaving for LP mitigation

Considering that the overall OFDM block consists of multiple subblocks, subblock interleaving can be a feasible way to reduce the impact of LP frequency response. As reported in [8], subblock interleaving can distribute the subcarriers of each subblock across the entire signal bandwidth, which can be easily conducted without any precoding or spreading procedures. Due to its inherent multi-carrier transmission nature, OSDMA can be easily realized to support multi-user communication for OFDM with index modulation systems with subblock interleaving.

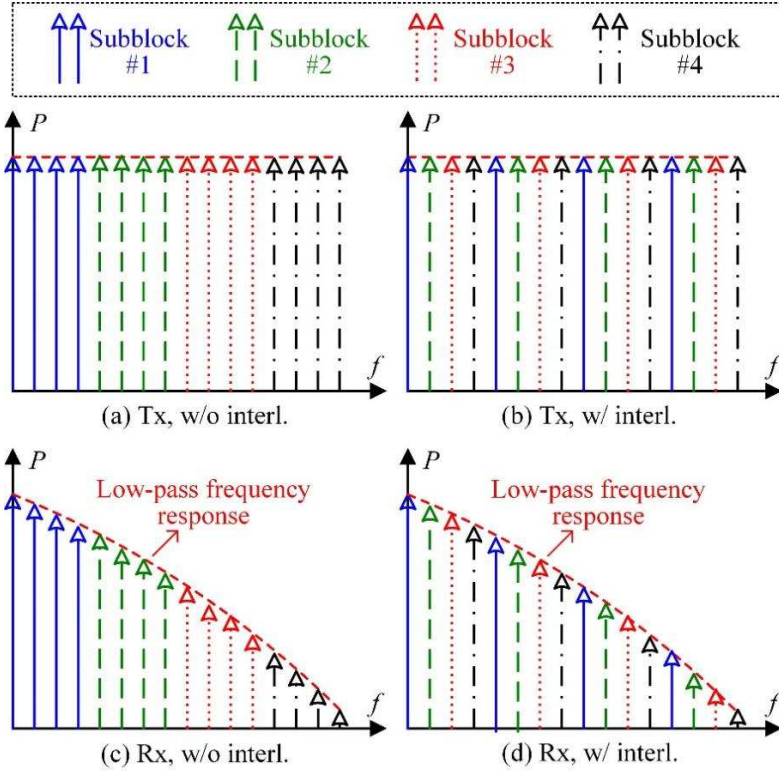


Figure 3. Illustration of OFDM-MMIM spectrum: (a) Tx, without interleaving, (b) Tx, with interleaving, (c) Rx, without interleaving, and (d) Rx, with interleaving.

Fig. 3 depicts the spectra of the transmitted/received OFDM-MMIM signals without/with subblock interleaving. For the case without interleaving, the high-frequency subblocks in the received signal will suffer from severe low-pass effect, which leads to a much higher BER in comparison to that of the low-frequency subblocks. In contrast, for the case with interleaving, the subcarriers within each subblock are distributed across the entire frequency region, and thus low-pass mitigation is realized.

### III. SIMULATION RESULTS

In this section, computer simulations are conducted for transmission performance evaluation of OFDM-MMIM in bandlimited LP-VLC systems, where both DFT spreading and subblock interleaving are considered and compared for LP mitigation.

Fig. 4 illustrates the electrical-optical-electrical (EOE) frequency response adopted for simulation in this work, which is actually measured from a practical experimental VLC system. As we can clearly see, the power attenuation reaches about 20 dB for a signal bandwidth of 50 MHz. Here, an additive white Gaussian noise (AWGN) channel with the adopted LP frequency response is considered for simulation.

For OFDM with MMIM, we assume that  $N=4$  and  $k=1$ , and three four-mode constellation designs are taken into consideration based on three 8-ary constellations including 8-QAM, 8-PSK, and (7,1)-QAM. Moreover, the length of IFFT/FFT is assumed to be 256, where 108 subcarriers are used to transmit valid data, and hence there are 27 subblocks within the OFDM block in total. The detailed simulation parameters are given in Table II.

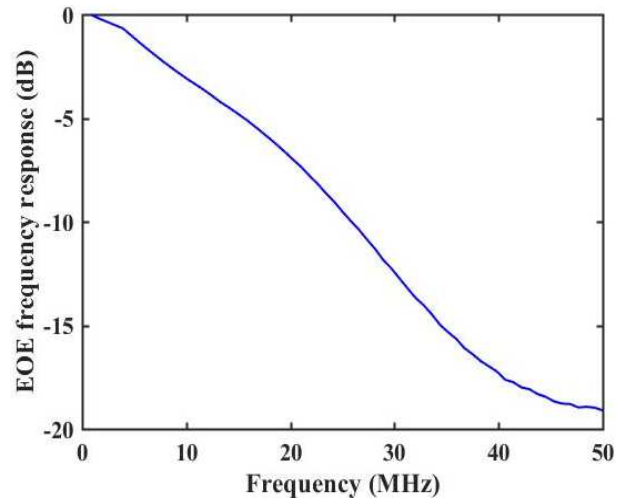


Figure 4. Adopted LP frequency response for simulation which is measure from a practical experimental VLC system.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
IFFT/FFT size	256
Subblock size	4
Number of data subcarriers	108
Number of subblocks	27
Signal bandwidth	50 MHz
Channel type	AWGN + LP
Base constellations	8-QAM, 8-PSK, (7,1)-QAM

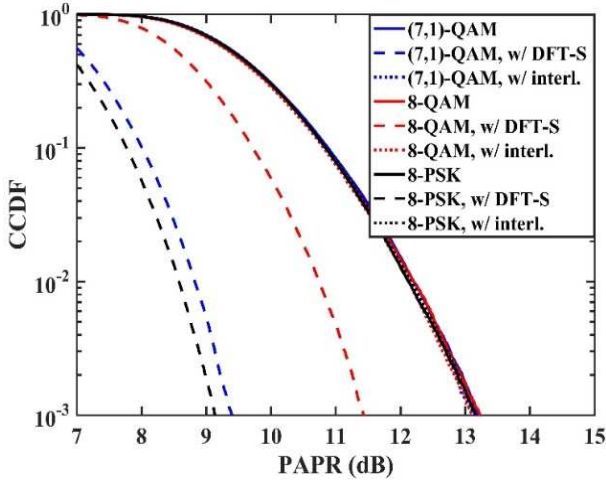


Figure 5. PAPR performance comparison of different schemes.

Fig. 5 compares the PAPR performance of different constellation design schemes with/without DFT spreading (DFT-S) or subblock interleaving (interl.). As can be seen, subblock interleaving cannot change the PAPR of the OFDM-MMIM signal, while DFT spreading is able to substantially reduce the PAPR of the OFDM-MMIM signal. More specifically, DFT spreading OFDM-MMIM (DFT-S-OFDM-MMIM) with 8-PSK achieves the lowest PAPR, while the PAPR of DFT-S-OFDM-MMIM with 8-QAM is about 2-dB higher than that with 8-PSK at a probability of  $10^{-3}$ . As a result, DFT spreading shows great potential for reducing the PAPR of OFDM-MMIM signals in the intensity-modulated VLC systems.

Fig. 6 shows the simulation BER vs. SNR for different constellation design schemes with/without DFT spreading (DFT-S) or subblock interleaving (interl.) over AWGN and LP channels. It can be found that the BERs over only AWGN channel without LP are significantly lower than that over AWGN channel with LP, suggesting that the LP frequency response has a very remarkable impact on the BER performance of OFDM-MMIM signals with all three four-mode constellation sets. Moreover, it is also found that (7,1)-QAM can achieve the best performance among all the constellation design schemes. For OFDM-MMIM with (7,1)-QAM, a signal-to-noise (SNR) increase of up to 11 dB at the BER threshold of  $3.8 \times 10^{-3}$ .

Fig. 7 further shows the simulation BER vs. SNR for different constellation design schemes with/without DFT spreading (DFT-S) or subblock interleaving (interl.) over the LP channel. As we can clearly observe, the BER performance with DFT spreading (DFT-S) is generally better than that with subblock interleaving for all the three four-mode constellation sets over the LP channel. Similarly, the lowest BER is always obtained by the OFDM-MMIM scheme with (7,1)-QAM. Particularly, for OFDM-MMIM with (7,1)-QAM, the SNRs required by using DFT spreading and subblock interleaving are 18.0 and 21.2 dB, respectively. Hence, an SNR gain of 3.2 dB is observed by using DFT spreading in comparison to that using subblock interleaving. It can be concluded from Fig. 7 that DFT spreading outperforms subblock interleaving in terms of BER performance. However, OFDM-MMIM with subblock interleaving can easily enable multi-user communication in VLC systems by

allocating different users with different subblocks via OSDMA.

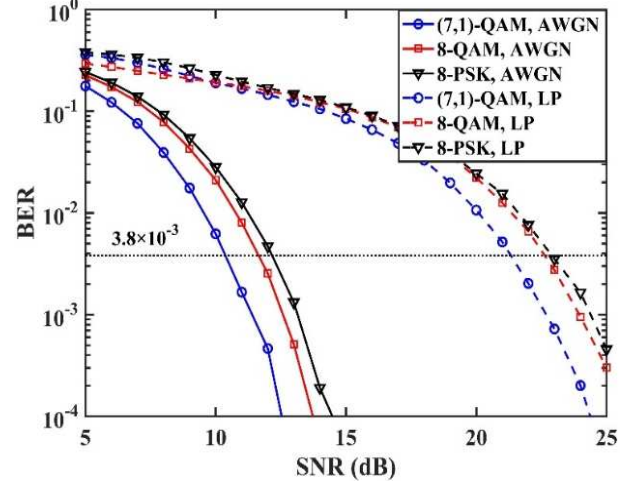


Figure 6. BER vs. SNR for different schemes over AWGN and LP channels.

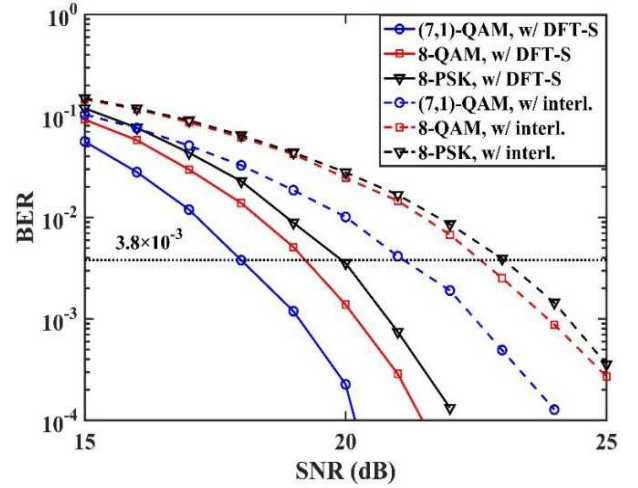


Figure 7. BER vs. SNR for different schemes over LP channel.

#### IV. CONCLUSION

In this paper, we have evaluated and compared the transmission performance of the OFDM-MMIM scheme in bandlimited LP-VLC systems using DFT spreading and subblock interleaving. Simulation results show that OFDM-MMIM with DFT spreading obtains better BER performance than that with subblock interleaving. In contrast, OFDM-MMIM with subblock interleaving can easily enable multi-user communication via OSDMA. Hence, both DFT spreading and subblock interleaving are promising techniques to enhance the overall performance of OFDM-MMIM in practical VLC systems.

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