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Dual-Mode Spatial Division Multiplexing with Geometric Constellation Shaping for UVLC

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***Abstract*—A dual-mode spatial division multiplexing (DM-SDM) scheme with geometric constellation shaping (GCS) is proposed for underwater visible light communication (UVLC) systems. Simulation and experimental results successfuly verify the superiority of DM-SDM with GCS for UVLC.**

***Index Terms*—Dual-mode index modulation, spatial division multiplexing, underwater visible light communication**

I. Introduction

Due to the advantages of low latency, high speed and high security, underwater visible light communication (UVLC) has been regarded as a promising solution for establishing robust wireless communication links in underwater environments [1]. Moreover, owing to its remarkable spectral efficiency and robustness against inter-symbol interference and frequency-selective fading, orthogonal frequency division multiplexing (OFDM) modulation has been widely used in UVLC systems [2], [3]. However, since OFDM modulation is the mutual superposition of all orthogonal subcarriers in one OFDM symbol, a high peak-to-average power ratio (PAPR) may be generated. Due to the influence of LED nonlinearity, a high PAPR will cause the modulation signal to act in the saturation region of the LED, resulting in distortion [4]. To solve this problem, subcarrier index modulation (IM) which improves the energy efficiency of traditional OFDM has attracted more and more attention [5]–[7]. Specifically, the transmission of information in this context involves utilizing both traditional constellations and subcarrier activation pattern [8]. However, in IM-OFDM systems, some subcarriers are deactivated which do not carry any information [7]. To further improve the system spectral efficiency, a dual-mode index modulation scheme aided OFDM (DM-OFDM), where the inactive subcarriers of OFDM-IM can transmit modulated symbols drawn from a secondary constellation, has been proposed by T. Mao [9]. It is proved that DM-OFDM significantly outperforms OFDM-IM in terms of bit error rate (BER) performance at the same spectral efficiency (SE). Moreover, a novel partitioning-based constellation design approach for DM-OFDM has been proposed in [4], and S. Sridhar has designed DM constellations by adjusting the power level and phase of two regular constellations in [10]. However, the previous constellation design schemes are all based on the division and deformation of traditional constellations, which could not fully tap the potential of DM constellations. In this paper, we propose a novel genetic algorithm (GA) to design the constellations of DM-IM with improved BER performance. Besides, for the first time, we employ DM-IM modulation in the spatial domain and propose dual-mode spatial division multiplexing (DM-SDM) scheme with GA-based geometric constellation shaping (GCS) for UVLC systems. The rest of this paper is organized as follows. Section II introduces the system model of the DM-SDM-UVLC system. Section III discusses the principle of GA-based GCS for DM-SDM-UVLC. In Section IV, simulation and experimental results are presented. Finally, Section V gives the conclusion of this paper.

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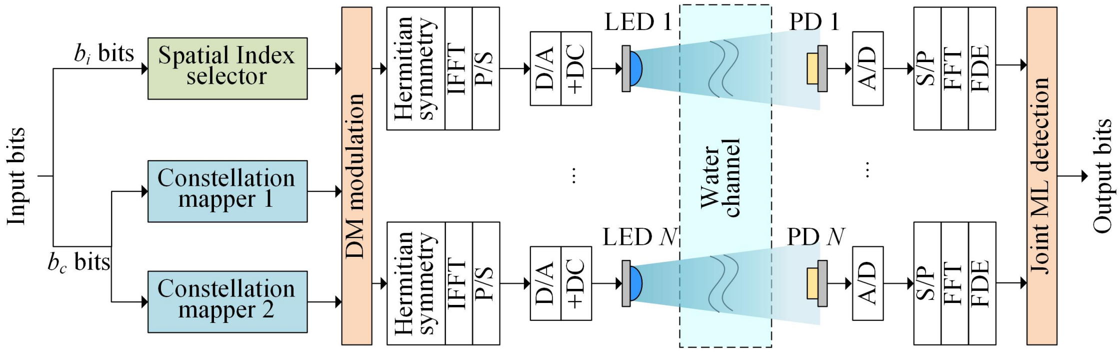

Fig. 1. Block diagram of the DM-SDM-based UVLC system.

II. System Model

The system model of the DM-SDM-UVLC system is illustrated in Fig. 1. Based on our previous works, SDM requires the same number of transmitters and receivers, and employing SDM in UVLC systems can increase the received optical power and significantly mitigate the inter-channel interference by establishing multiple parallel spatial sub-channels [11]. As can be seen, at the transmitter side, the input data are first divided into b_i spatial mapping bits and b_c constellation mapping bits, and b_i and b_c can be denoted as

$$\begin{aligned} b_i &= \lfloor \log_2(C(N,k)) \rfloor \\ b_c &= k\log_2(M_1) + (N-k)\log_2(M_2) \end{aligned} \tag{1}$$

where $C(\cdot)$ denotes the binomial coefficient, N is the number of sub-channels and k is the number of the selected sub-channels. Moreover, M_1 and M_2 represent the sizes the two distinguishable constellation sets $\mathbf{M}_1 = \{S_1^1, S_2^1, \ldots, S_i^1\}$ and $\mathbf{M}_2 = \{S_1^2, S_2^2, \ldots, S_i^2\}$, respectively, and we have $\mathbf{M}_1 \cap \mathbf{M}_2 = \varnothing$. Through DM modulation, the spatial mapping bits can be conveyed implicitly by the indices of sub-channels modulated by the same constellation alphabet, and the constellation mapping bits are transmitted by channels are modulated by M_2. The mapping table of DM modulation for N = 2 and k = 1 is given in Table I. After imposing Hermitian symmetry (HS), inverse fast Fourier transform (IFFT) and parallel-to-serial (P/S) conversion, real-values serial signal streams are generated. Then each digital signal stream is converted into an analog signal stream via digital-to-analog (D/A) conversion and a DC bias is further added to ensure the non-negativity of the analog signal stream which can be directly loaded into each LED. After propagating through a water channel, the optical signals eventually arrive at the receiving end. At the receiver, the detected optical signals using photo-detectors (PDs) are converted to electric signals, and after analog-to-digital (A/D) conversion, serial-to-parallel (S/P) conversion and FFT, frequency domain equalization (FDE) is employed. The equalized signals in each receiver are jointly detected by joint maximum likelihood (ML) detection to recover the original signals [12]. Finally, according to the mapping table, the output data can be obtained.

TABLE I
Mapping Table of DM-SDM for N = 2 and k = 1

Index bit	Spatial channel index for M_1	DM-SDM symbol
0	1	$[S_i^1, S_i^2]$
1	2	$[S_i^2, S_i^1]$

III. Princípe of GA-Based GCS for DM-SDM-UVLC

In this section, we propose a GA-based GCS for the DM-SDM-UVLC system. The GA is grounded on the principle of simulating the evolutionary process and natural selection observed in populations in nature. Through successive generations of evolution, only the fittest individuals can survive and thrive in their environment, eventually leading to the emergence of superior individuals [13]. Fig. 2 shows the flow chart of GA, where the initial population is a $(M_1 + M_2)$-point constellation, which is produced by normalized random complex symbols following the complex Gaussian distribution. Offspring pairs are created by applying the crossover operation to each pair of parent individuals. Following this, new individuals for the next generation are generated through mutation at a rate of P_m. The DM-SDM-UVLC system can be regarded as the environment and the simulation BER is defined as the fitness of each individual. The parameters of the DM-SDM-UVLC system are given in Table II. On the grounds of this system, the fitness of each individual can be calculated. Then the individuals with high fitness are selected to be initial population for the next iteration by employing a selection strategy. Finally, until reaching the iterations, the individual with the lowest BER can be obtained.

TABLE II
Basic Parameters of DM-SDM-UVLC System

Parameter	Value
Number of data subcarriers, N_{data}	92
IFFT/FFT points, N_F	256
Number of subchannels, N	2
Selected subchannels, k	1
SNR	8 dB
Size of $\mathbf{M_1}$, M_1	4
Size of $\mathbf{M_2}$, M_2	4

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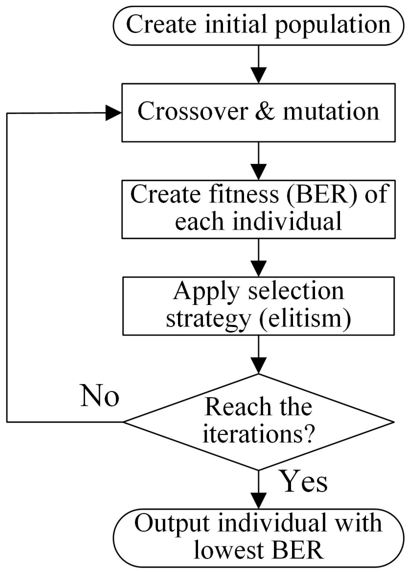

Fig. 2. Flow chart of the genetic algorithm (GA).

IV. Results and Discussions

In this section, we compare the performance of DM-SDM-UVLC systems with and without applying GA-based GCS. For comparison, the SDM-UVLC system without employing DM modulation is also considered. In both simulation and experiment, there are $N = 2$ independent spatial channels in the SDM-UVLC system, the length of IFFT/FFT is set to 256 and the number of selected subchannels to transmit mode 1 is $k = 1$. Fig. 3 shows the traditional constellations and GA-generated constellations of mode 1 and mode 2, respectively, where $M_1 = 4$ and $M_2 = 4$.

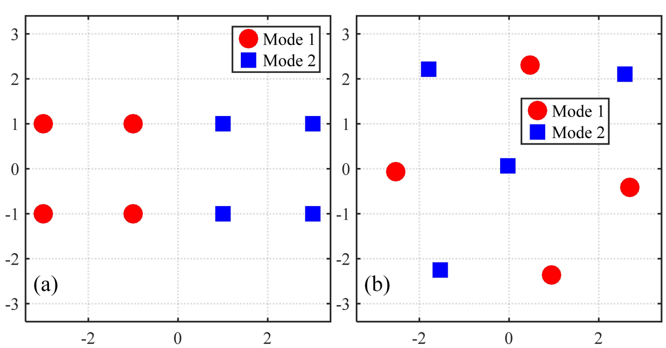

Fig. 3. DM constellation diagram: (a) generated by dividing traditional constellation diagram, (b) generated by GA.

A. Simulation results

Fig. 4 illustrates the simulation BER versus SNR for SDM and DM-SDM using optimal constellation and traditional constellation with the same spectral efficiency of 5 bits/s/Hz in the UVLC system. To achieve the same spectral efficiency, one of the SDM channels is modulated with 8-QAM and the other channel is modulated with 4-QAM. As we can see, the BER performance of DM-SDM without GCS is worse than that of SDM, but the BER performance of DM-SDM with GCS can be significantly improved. To reach the 7% forward error correction (FEC) coding limit of BER $= 3.8^{-3}$, the required SNR of DM-SDM with GCS is 1.7 dB lower than that of SDM, which is 2.4 dB lower than that of DM-SDM without GCS.

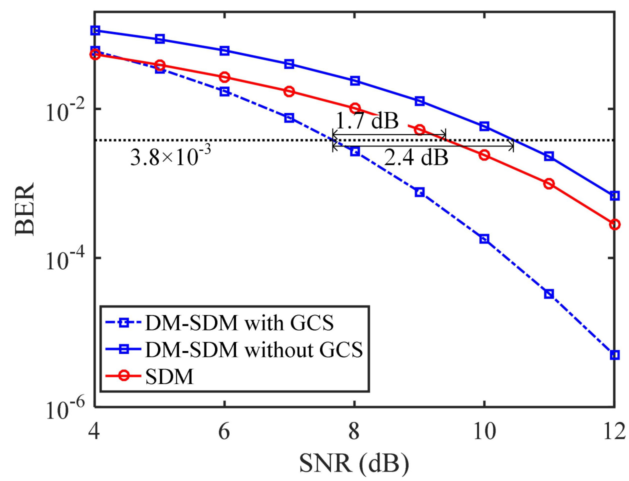

Fig. 4. Simulated BER vs. received SNR.

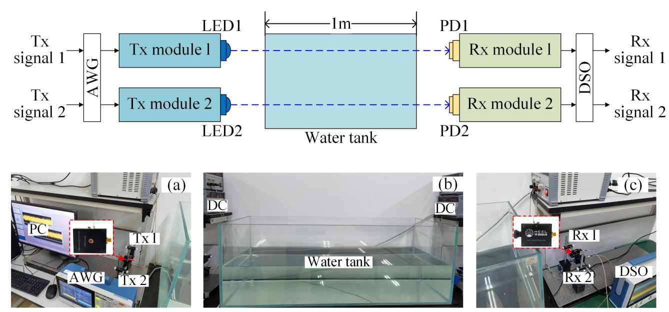

Fig. 5. Experimental setup of the two-channel UVLC system using two pairs of commercially available Tx and Rx modules. Insets: photos of (a) the Tx side, (b) the overall system, and (c) the Rx side.

B. Experimental results

We further experimentally study the BER performance of the DM-SDM-UVLC system with and without GCS. Fig. 5 describes the experimental setup and the photos of DM-SDM UVLC system using two pairs of commercial blue LED transceiver modules. The Tx signals generated offline by MATLAB are first loaded into the arbitrary waveform generator (AWG, Tektronix AFG31102). Then the output electric signals are fed into two Tx modules, respectively. The Tx modules are powered by 12V driving currents. After propagating through a 1m water tank, the signals are detected by two Rx modules, which are also powered by 12V driving currents. Afterward, the digital storage oscilloscope (DSO, Tektronix MDO32) records the output electrical signal of the

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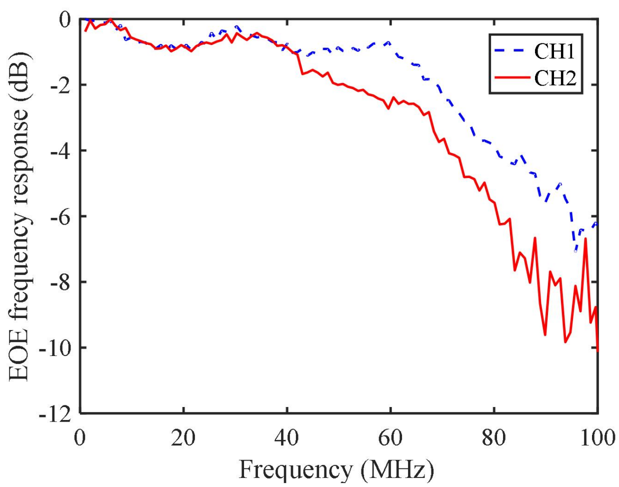

Fig. 6. Measured EOE frequency responses of two spatial channels in the experimental UVLC system.

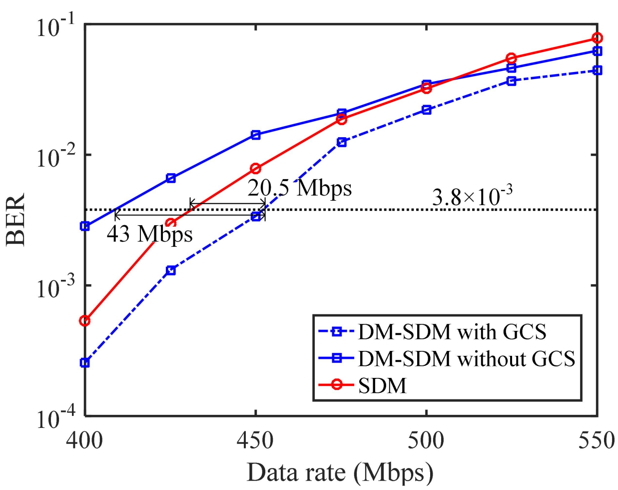

Fig. 7. Experimental BER vs. data rate.

PD at a sampling rate of 1.25 GSa/s. The resulting digital signal is then processed offline in MATLAB. The measured frequency responses of the two spatial channels are depicted in Fig. 6. Moreover, Fig. 7 shows the experimental BER versus data rate for a spectral efficiency of 5 bits/s/Hz. When the date rate is less than 500 Mbps, DM-SDM without GCS exhibits worse BER performance compared to SDM. However, by using GCS, the BER performance of DM-SDM is significantly improved, enabling it to achieve the best performance. More specifically, the maximum achievable data rate that satisfies the FEC limit can reach 450 Mbps, which is 20.5 Mbps higher than SDM and 43.0 Mbps higher than DM-SDM without GCS.

V. Conclusion

In this paper, we have proposed and evaluated a novel DM-SDM scheme with a GA-GCS for UVLC system. Both simulation and experimental results show that the proposed DM-SDM scheme with GA-GCS can achieve a significant BER improvement compared to other benchmark schemes.

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