

DHT-OFDM Based Spatial Modulation for Optical Wireless Communication

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Abstract—The combination of orthogonal frequency division multiplexing (OFDM) and spatial modulation (SM) can enhance the capacity of optical wireless communication (OWC) systems with low complexity. In this paper, we propose a novel SM scheme for intensity modulation/direct detection (IM/DD) OWC systems by employing discrete Hartley transform based OFDM (DHT-OFDM). Due to the use of DHT with one-dimensional constellations, the Hermitian symmetry constraint, which is generally imposed in conventional discrete Fourier transform based OFDM (DFT-OFDM) to obtain a real-valued output signal, is not required in DHT-OFDM. As a result, DHT-OFDM based SM can achieve much higher spectral efficiency than that of DFT-OFDM based SM in OWC systems. Simulation results show that, for an indoor 4×4 SM-OWC system with a spectral efficiency of 6 bits/s/Hz, DHT-OFDM achieves a remarkable 4.5-dB transmit signal-to-noise ratio reduction for an overall bit error rate of 10^{-3} in comparison to conventional DFT-OFDM.

Keywords—spatial modulation; orthogonal frequency division multiplexing; optical wireless communication

I. INTRODUCTION

Due to the rapid growth of smart mobile devices which demand high definition video streaming, low-latency gaming and virtual/augmented reality in our daily life, the mobile data traffic is exponentially increased in recent years. However, the existing radio frequency (RF) spectrum will be saturated in the near future. In order to support the ever-increasing mobile data traffic, it might be necessary to exploit the higher frequency of the electromagnetic spectrum, i.e., the optical spectrum including visible light, infrared and ultra-violet [1]. As a very promising candidate to satisfy the demand of heavy mobile data traffic for mobile users, optical wireless communication (OWC) has attracted great attention lately [2]. Typical OWC systems use laser diodes (LDs) or light-emitting diodes (LEDs) as transmitters and photo-diodes (PDs) as receivers, which generally adopt intensity modulation with direct detection (IM/DD) for signal transmission [3].

Commercial off-the-shelf optical elements usually have very limited electrical bandwidth, and hence various capacity-enhancement techniques have been applied in OWC systems to achieve high capacity. Among them, orthogonal frequency division multiplexing (OFDM) modulation using high-order quadrature amplitude modulation (QAM) constellations and multiple-input multiple-output (MIMO) transmission are two

most popular techniques [4]–[8]. Due to the IM/DD nature of OWC systems, the Hermitian symmetry constraint is usually imposed in OFDM modulation so as to obtain a real-valued signal and a direct current (DC) bias is usually added to convert the bipolar signal into a non-negative unipolar signal for intensity modulation in LD/LED transmitters. Moreover, mainly three types of MIMO transmission schemes can be applied in OWC systems, including repetition coding (RC), spatial multiplexing (SMP) and spatial modulation (SM) [6]. RC is the simplest MIMO scheme which can provide transmit diversity for OWC systems, but with the lowest spectral efficiency. SMP can provide high spectral efficiency, but suffers from severe inter-channel interference (ICI) due to channel correlation and high detection complexity. As a digitized MIMO scheme, SM has the advantages of reduced ICI, increased power efficiency and low detection complexity compared with SMP [9]. Nevertheless, the spectral efficiency of SM is relatively lower than SMP.

The combination of OFDM and SM has been shown as an efficient way to enhance the capacity of bandlimited OWC systems with low complexity, where SM can be implemented in the frequency domain or in the time domain [10], [11]. Although OFDM with time-domain SM can achieve higher spectral efficiency than that with frequency-domain SM, it requires a secondary DC bias to avoid zero samples after zero clipping, which might reduce the power efficiency of the system [12]. To improve the spectral efficiency of bandlimited OWC systems employing OFDM with frequency-domain SM, in this paper, we propose a novel SM scheme based on discrete Hartley transform based OFDM (DHT-OFDM). By utilizing DHT with one-dimensional constellations, the Hermitian symmetry constraint in discrete Fourier transform based OFDM (DFT-OFDM) can be eliminated [13], and hence the spectral efficiency can be greatly increased in bandlimited OWC systems. The superiority of DHT-OFDM over DFT-OFDM has been verified in a typical indoor 4×4 SM-OWC system via numerical simulations.

II. SYSTEM MODEL

In this section, we introduce the model of a general IM/DD SM-OWC system using OFDM modulation. The model of a typical MIMO OWC channel is first described and then two different IM/DD SM-OWC systems based on DFT-OFDM and DHT-OFDM are respectively discussed.

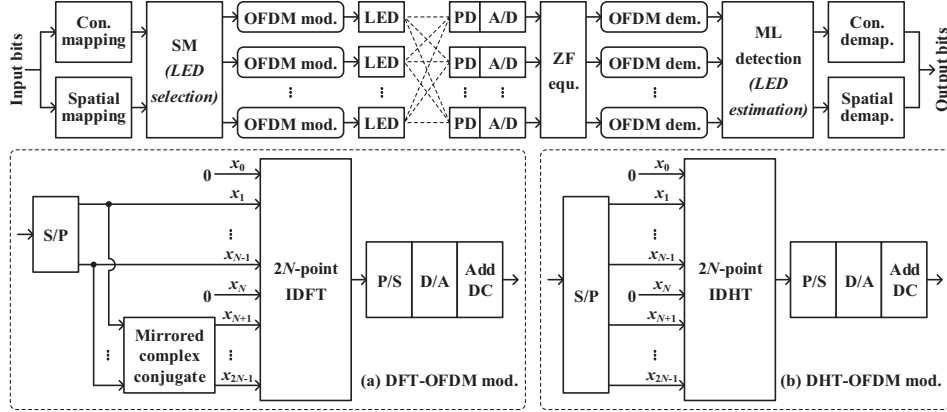


Figure 1. Schematic diagram of an IM/DD SM-OWC system using OFDM modulation. Insets: (a) DFT-OFDM modulator; (b) DHT-OFDM modulator. (Con.: constellation; mod.: modulation; equ.: equalization; dem.: demodulation; demap.: demapping).

A. Channel Model

For a typical indoor IM/DD SM-OWC system with N_t transmitters (e.g., LEDs) and N_r receivers (e.g., PDs), the received signal vector $\mathbf{y} = [y_1, y_1, \dots, y_{N_r}]^T$ can be expressed by

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \quad (1)$$

where $\mathbf{H}$ is the channel matrix, $\mathbf{s} = [s_1, s_2, \dots, s_{N_t}]^T$ is the transmitted signal vector and $\mathbf{n} = [n_1, n_2, \dots, n_{N_r}]^T$ is the additive noise vector. Let h_{rt} denote the r -th row and the t -th column element of $\mathbf{H}$ with $r = 1, 2, \dots, N_r$ and $t = 1, 2, \dots, N_t$. Assuming only line-of-sight (LOS) transmission and each LED transmitter follows a Lambertian radiation pattern, the LOS DC channel gain between the r -th PD and the t -th LED can be calculated by

$$h_{rt} = \frac{(m+1)\rho A}{2\pi d_{rt}^2} \cos^m(\varphi_{rt}) T(\theta_{rt}) g(\theta_{rt}) \cos(\theta_{rt}), \quad (2)$$

where $m = -\ln(2)/\ln(\cos\Phi)$ is the Lambertian emission order with Φ being the semi-angle at half power of the LED transmitter; ρ is the responsivity of the PD; A is the active area of the PD; d_{rt} is the distance between the r -th PD and the t -th LED; φ_{rt} and θ_{rt} are the emission angle and the incident angle, respectively; $T(\theta_{rt})$ is the optical filter gain; $g(\theta_{rt}) = n^2/\sin^2\psi$ is the optical lens gain, where n and ψ are the refractive index and the half-angle field-of-view (FOV) of the optical lens, respectively.

In order to estimate the transmitted signal vector $\mathbf{s}$ from the received signal vector $\mathbf{y}$, zero forcing (ZF) based equalization is usually performed and the resultant estimate of $\mathbf{s}$ is obtained by

$$\mathbf{s}^* = \mathbf{H}^+ \mathbf{y} + \mathbf{n} = \mathbf{s} + \mathbf{H}^+ \mathbf{n}, \quad (3)$$

where $\mathbf{H}^+$ is the pseudo inverse of $\mathbf{H}$ [4].

In typical SM-OWC systems, the additive noise includes thermal and shot noises [6] and it is reasonable to model the additive noise as a real-valued additive white Gaussian noise (AWGN) with zero mean and power $P_n = N_0 B$, where N_0 and

B represent the noise power spectral density (PSD) and the system modulation bandwidth, respectively.

B. OFDM Based IM/DD SM-OWC

Fig. 1 illustrates the schematic diagram of an IM/DD SM-OWC system using OFDM modulation. As we can see, the input bits are first separated into two streams: one stream is mapped into constellation symbols and the other is mapped into spatial symbols. After that, SM is performed in the frequency domain where single LED selection is carried out in the subcarrier level [12]. At each subcarrier slot, only one OFDM modulator corresponding to the selected LED is employed to transmit the M -ary constellation symbol and the inputs of the remaining $N_t - 1$ OFDM modulators are set to zero. The outputs of N_t OFDM modulators are then utilized to drive N_t LED transmitters, respectively. After free-space propagation, N_r PDs are used to capture the light and N_r digital signals can be obtained via analog-to-digital (A/D) conversion. Subsequently, ZF equalization and OFDM demodulation are performed. At each subcarrier slot, we adopt maximum-likelihood (ML) detection to estimate the index of the selected LED transmitter in the frequency domain. Hence, both the transmitted constellation and spatial symbols can be recovered for demapping to obtain the output bits.

1) *DFT-OFDM Based SM-OWC*: Due to the IM/DD nature of SM-OWC systems, the driving signal of each LED transmitter should be real-valued and non-negative. DFT-OFDM with the Hermitian symmetry constraint is the commonly applied OFDM modulation scheme in IM/DD SM-OWC systems [12]. The inset (a) in Fig. 1 shows the principle of DFT-OFDM modulator. For a $2N$ -point IDFT, x_0 and x_N are corresponding to the DC component, and only $N - 1$ inputs (i.e., $x_1, \dots, x_{N-1}$) can be used to carry valid data, while the other $N - 1$ inputs (i.e., $x_{N+1}, \dots, x_{2N-1}$) are utilized to transmit the mirrored complex conjugate of the same data. Therefore, when the value of N is relatively large, the spectral efficiency (bits/s/Hz) of DFT-OFDM based SM-OWC systems with N_t LEDs and two-dimensional M -QAM constellation is given by

$$\eta_{\text{DFT-OFDM}} \approx \frac{1}{2} (\log_2 M + \text{floor}(\log_2 N_t)), \quad (4)$$

where $\text{floor}(\cdot)$ is the floor operator which outputs an integer smaller or equal to its input value. In Eq. (4), the first term is contributed by the constellation bits which are carried by the adopted M -QAM constellation, while the second term is contributed by the spatial bits through LED index selection in the frequency domain. The scaling factor $1/2$ is due to the imposing of Hermitian symmetry constraint in DFT-OFDM.

The parallel outputs of inverse DFT (IDFT) are converted into a serial signal via parallel-to-serial (P/S) conversion, and a real-valued bipolar signal is obtained after digital-to-analog (D/A) conversion. Subsequently, a DC bias is added to convert the bipolar signal into an LED-compatible non-negative signal. The DFT-OFDM demodulation is the inverse process of the DFT-OFDM modulation, which is omitted here for brevity.

2) *DHT-OFDM Based SM-OWC*: Due to the Hermitian symmetry constraint imposed in conventional DFT-OFDM, the number of IDFT inputs that can be used to transmit valid data is only about half of the IDFT size. In order to eliminate the Hermitian symmetry constraint and hence improve the overall spectral efficiency of OFDM based IM/DD SM-OWC systems, we replace DFT-OFDM with DHT-OFDM by adopting DHT with one-dimensional M -ary pulse amplitude modulation (M -PAM) constellation and propose a novel DHT-OFDM based SM scheme for IM/DD OWC systems.

The principle of DHT-OFDM modulator is shown in the inset (b) of Fig. 1. It can be seen that, for a $2N$ -point inverse DHT (IDHT), the number of IDHT inputs that can be used to transmit valid data is increased to $2(N-1)$, since no Hermitian symmetry constraint is required at the input of IDHT [13]. As a result, the spectral efficiency of DHT-OFDM based SM-OWC systems with N_t LEDs and one-dimensional M -PAM constellation can be obtained by

$$\eta_{\text{DHT-OFDM}} \approx \log_2 M + \text{floor}(\log_2 N_t). \quad (5)$$

Similarly, the first and second terms in Eq. (5) are contributed by the M -PAM constellation bits and the spatial bits via subcarrier-level LED index selection, respectively. By comparing Eqs. (4) and (5), we can see that the scaling factor $1/2$ is eliminated by replacing DFT-OFDM with DHT-OFDM. More specifically, DFT-OFDM with M^2 -QAM constellation and DHT-OFDM with M -PAM constellation can provide the same number of constellation bits while maintaining comparable bit error rate (BER) performance [13]. However, DHT-OFDM can achieve a doubled number of spatial bits compared with DFT-OFDM, which leads to a substantially improved overall spectral efficiency of OFDM based IM/DD SM-OWC systems.

TABLE I. REQUIRED CONSTELLATIONS FOR DFT-OFDM AND DHT-OFDM TO ACHIEVE THE SAME SPECTRAL EFFICIENCY

OFDM Scheme	Spectral efficiency		
	4 bits/s/Hz	5 bits/s/Hz	6 bits/s/Hz
DFT-OFDM	64QAM	256QAM	1024QAM
DHT-OFDM	4PAM	8PAM	16PAM

III. PERFORMANCE EVALUATION AND COMPARISON

In this section, we evaluate and compare the performance of DFT-OFDM and DHT-OFDM based IM/DD SM-OWC systems in a typical indoor environment through simulations. We consider a 4×4 SM-OWC system, i.e., $N_t = N_r = 4$, in a $5 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$ room. The 2×2 square LED array is mounted in the ceiling and the user equipped with a 2×2 square PD array is located over the receiving plane which is 0.85 m above the floor. We assume that the LED transmitters are oriented downwards to point straight to the receiving plane and the PDs are vertically oriented towards the ceiling. The center of the LED array is $(2.5 \text{ m}, 2.5 \text{ m}, 3 \text{ m})$ and the spacing between two adjacent LEDs in the square LED array is 2 m . The user with the PD array is located at $(2 \text{ m}, 2 \text{ m}, 0.85 \text{ m})$ and the spacing between two adjacent PDs in the square PD array of the user is 10 cm . The semi-angle at half power of each LED is 60° . The gain of the optical filter is 0.9 . The refractive index and the half-angle FOV of the optical lens are 1.5 and 72° , respectively. The responsivity and the active area of each PD are 0.53 A/W and 1 cm^2 , respectively. The modulation bandwidth is set to be 20 MHz and the noise PSD is $10^{-22} \text{ A}^2/\text{Hz}$.

We first analyze the achievable spectral efficiency of the 4×4 SM-OWC system using different OFDM modulation schemes. According to Eqs. (4) and (5), Table I summarizes the required constellations for DFT-OFDM and DHT-OFDM to achieve the same spectral efficiency in the 4×4 SM-OWC system. Specifically, to achieve a spectral efficiency of 4 bits/s/Hz , DFT-OFDM needs to adopt 64QAM while DHT-OFDM only requires 4PAM. For a higher spectral efficiency such as 6 bits/s/Hz , the QAM order required by DFT-OFDM is as large as 1024 while the PAM order required by DHT-OFDM is only 16. As we can see, to achieve the same spectral efficiency, the required constellation order can be significantly reduced by replacing DFT-OFDM with DHT-OFDM, which is due to the elimination of the Hermitian symmetry constraint in DHT-OFDM modulation.

We further investigate the BER performance of the 4×4 SM-OWC system using DFT-OFDM and DHT-OFDM. Fig. 2 shows the BER performance versus the transmit SNR (i.e., the SNR at the transmitter side [6]) for the 4×4 SM-OWC system using DFT-OFDM and DHT-OFDM with different spectral efficiencies. For a spectral efficiency of 4 bits/s/Hz , as shown in Fig. 2(a), the BER of spatial symbols for DHT-OFDM is higher than that of DFT-OFDM when the transmit SNR is relatively small, and a comparable BER of spatial symbols can be achieved when the transmit SNR is about 164 dB . With the further increase of transmit SNR, DHT-OFDM outperforms DFT-OFDM in terms of the BER of spatial symbols. However, the BER of 4PAM constellation symbols for DHT-OFDM is significantly lower than that of 64QAM constellation symbols for DFT-OFDM. To achieve an overall BER of 10^{-3} , the required transmit SNRs for DFT-OFDM and DHT-OFDM are 164.7 dB and 167.9 dB , respectively, indicating a transmit SNR reduction of 3.2 dB by using DHT-OFDM in comparison to conventional DFT-OFDM.

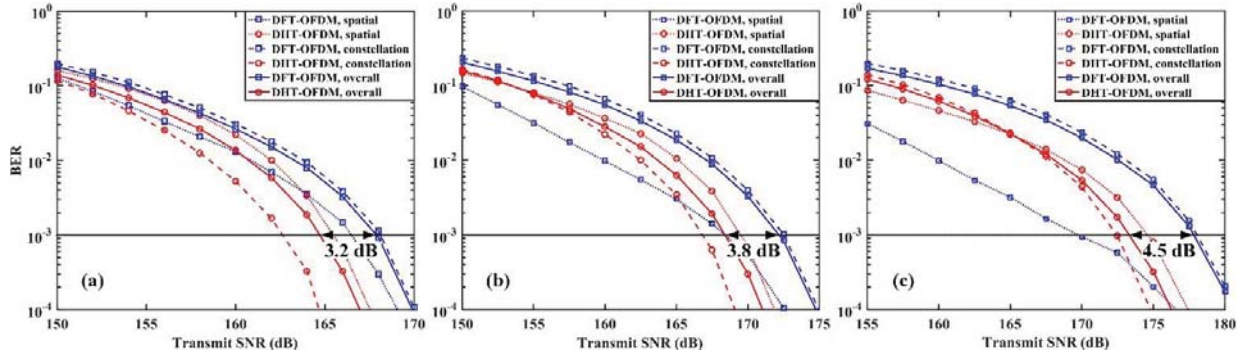


Figure 2. BER vs. transmit SNR for the 4×4 SM-OWC system using DFT-OFDM and DHT-OFDM with a spectral efficiency of (a) 4 bits/s/Hz, (b) 5 bits/s/Hz and (c) 6 bits/s/Hz.

Figs. 2(b) and (c) compare the BER performance of the 4×4 SM-OWC system using DFT-OFDM and DHT-OFDM with spectral efficiencies of 5 and 6 bits/s/Hz, respectively. It can be observed that DFT-OFDM outperforms DHT-OFDM in terms of the BER of spatial symbols when the transmit SNR is relatively small. Nevertheless, the BER gap of spatial symbols becomes negligible with the increase of transmit SNR and the BER of spatial symbols for DHT-OFDM will be lower than that for DFT-OFDM when the transmit SNR is relatively large. In contrast, DHT-OFDM greatly outperforms DFT-OFDM in terms of the BER of constellation symbols for a high spectral efficiency. Hence, much lower overall BERs can be achieved by DHT-OFDM in comparison to DFT-OFDM in the 4×4 SM-OWC system for relatively higher spectral efficiencies. More specifically, the transmit SNR reduction to achieve an overall BER of 10^{-3} is increased from 3.2 to 3.8 dB when the spectral efficiency is increased from 4 to 5 bits/s/Hz, and a more remarkable transmit SNR reduction of 4.5 dB is obtained with a spectral efficiency of 6 bits/s/Hz. It can be concluded that a more significant transmit SNR reduction can be achieved for a higher spectral efficiency.

IV. CONCLUSION

In this paper, we have proposed and evaluated a novel DHT-OFDM based SM scheme for IM/DD OWC systems. By replacing conventional two-dimensional constellation based DFT-OFDM with one-dimensional constellation based DHT-OFDM, the Hermitian symmetry constraint can be eliminated and hence the achievable spectral efficiency of the SM-OWC systems is greatly enhanced. Simulation results verify that significant transmit SNR reductions can be achieved by using DHT-OFDM in comparison to DFT-OFDM for the same spectral efficiency in a typical indoor 4×4 SM-OWC system. Therefore, the proposed DHT-OFDM based SM scheme can be a promising candidate for future high-speed OWC systems.

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