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An Improved Performance of 2D ASCO-OFDM in Wireless Communication

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Abstract— *This paper describes a novel modulation scheme of asymmetrically and symmetrically clipping optical (ASCO)-OFDM into two dimensional (2D) intensity modulation direct detection (IM/DD) optical wireless communications (OWC). The asymmetrically clipping optical (ACO)-OFDM symbols and the symmetrically clipping optical (SCO)-OFDM symbols are mapped into odd columns and even columns of transmitted matrices respectively. Due to an ASCO-OFDM signal consists of an ACO-OFDM signal and a SCO-OFDM signal, the average data rate of ASCO-OFDM is higher than that of ACO-OFDM. An improved receiving technique for the asymmetrically and symmetrically clipping optical (ASCO)-OFDM is developed for wireless communication system. Analysis found that the interference caused by clipping only affects the symbols on the even subcarriers. At the receiver, the ACO-OFDM symbols can be easily obtained by detecting the data on the odd subcarriers; the SCO-OFDM symbols can be successfully recovered by subtracting the estimated ACO-OFDM clipping noise and the SCO-OFDM clipping noise from the even subcarriers. The ACO-OFDM clipping noise is estimated from the received ACO-OFDM signals, and it can be reused to decrease the symbol error rate (SER) of ACO-OFDM signals. The SER of SCO-OFDM signals depend on the precision of ACO-OFDM signals. Thus, we apply an improved ACO-OFDM receiving technique in our current receiver to further improve the SER performance of SCO-OFDM signals as well as that of the whole system. We show that the spectral efficiency of 2D ASCO-OFDM is twice as much as that of other OFDM modulation schemes. The major problem of OFDM high Peak-to-Average power ratio (PAPR) is reduced by 2dB. The channel capacity of ASCO-OFDM in AWGN channel is calculated. The symbol error rate (SER) performance of 2D ASCO-OFDM is simulated under the environment of additive white Gaussian noise (AWGN) and it exhibits better SER performance than 2D ACO-OFDM and 2D ADO-OFDM in the same bit rate case.*

Keywords— *ACO-OFDM, ADO-OFDM, ASCO-OFDM, IM/DD, OFDM, OWC, SCO-OFDM, SER.*

I. INTRODUCTION

Optical wireless communication (OWC) has been widely studied in recent decade because it can be an effective alternative to radio frequency communication (RFC) for indoor wireless applications. Intensity modulation and direct detection (IM/DD) can be simply implemented into optical wireless systems. The information stream is modulated into the intensity of optical carriers, and the optical signals are transmitted by LED emitters. The intensity variation of optical signal will be detected by a photodiode and the received optical signals are converted to electrical signals for decoding. However, most experiments are developed over single-input single-output (SISO) systems. In the meantime, the two dimensional (2D) optical wireless system, which is a form of multiple-input multiple-output (MIMO), also has been studied and they are getting more and more attentions.

Orthogonal frequency division multiplexing (OFDM) has been extensively applied into IM/DD optical wireless systems because it is capable of combating the inter-symbol-interference (ISI) caused by multipath transmission, especially in an indoor environment. As we adopt IM/DD to realize the transmission and reception, the optical signals must be real and non-negative. In order to obtain real signals, blocks of complex symbols in the frequency domain must be constraint to Hermitian symmetry. Then two modulation schemes, asymmetrically clipping optical (ACO)-OFDM and DC biased optical (DCO)-OFDM, have been adopted to make the real signals non-negative in one dimensional (1D) optical systems. Also, these two techniques have been investigated in 2D optical wireless systems. By adding an appropriate DC bias to remove the negative values. However, it has been shown that DCO-OFDM is not optical power efficient, and the performance highly depends on the DC bias level in 1D OWC. ACO-OFDM is much more optical power efficient than DCO-OFDM, but it requires twice bandwidth as much as DCO-OFDM does. Additionally, the ACO-OFDM transmitted signals inherently have a large PAPR.

Asymmetrically and symmetrically clipping optical (ASCO)-OFDM is an improved clipping OFDM modulation scheme for optical wireless systems. We first map ACO-OFDM symbols onto the odd subcarriers. In order to improve the bandwidth efficiency, SCO-OFDM symbols are modulated onto the even subcarriers. A transmitted ASCO-OFDM signal is the sum of an ACO-OFDM signal and a SCO-OFDM signal. Since the clipping noises fall onto the even subcarriers without distorting the odd subcarriers, we can directly detect the symbols on the odd subcarriers to recover ACO-OFDM symbols. After subtracting the estimated ACO-OFDM clipping noise from even subcarriers, we finally obtain the SCO-OFDM symbols. This scheme, ASCO-OFDM, not only improves the bandwidth efficiency but also reduces the PAPR of transmitted optical signals. Here we apply ASCO-OFDM into 2D optical systems to improve the performances in terms of the PAPR and SER.

II. SYSTEM MODEL AND ASSUMPTIONS

A. 2D ACO-OFDM

The block diagram of a 2D ACO-OFDM system is shown in figure 1. Blocks of electrical symbols drawn from constellations, such as 4-QAM, 16-QAM, and 64-QAM, are input to the system. Conventionally, the symbols are mapped into a signal vector in 1D optical wireless system. In the 2D case, the input symbols are mapped into N1xN2 signal matrix

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as follows:

$$S_{N1\times N2}=\begin{bmatrix} S_{00} & S_{01} & . \; . & S_{0,N2-1} \\ S_{10} & S_{11} & . \; . & S_{1,N2-1} \\ & . & & \\ . & . & . \; . \; . & \\ & . & & \\ . & . & . \; . \; . & \\ S_{N1-1,0} & S_{N2-1,1} & . \; . & S_{N1-1,N2-1} \end{bmatrix}$$

where N1 and N2 are even numbers. This matrix is taken by a 2D IFFT to transform it into the time domain to yield s_{N1XN2}

$$s_{N1xN2}=\begin{bmatrix} s_{01} & s_{01} & . \; . & s_{0,N2-1} \\ s_{10} & s_{11} & . \; . & s_{1,N2-1} \\ . & . & . \; . & \\ . & . & . \; . & \\ s_{N1-1,0} & s_{N2-1,1} & . \; . & s_{N1-1,N2-1} \end{bmatrix}$$

In this paper, the upper cases represent frequency domain symbols and the lower cases represent time domain signals. In order to ensure each value in the matrix real, the elements in matrix S must have 2D Hermitian symmetry constraint, which is defined as follows:

$$S\,(k1, k2) = S^{*}(N1-1-k1, N2-1-k2)$$

The elements $S_{0,N}$ in the first row and the elements $S_{0,M}$ in the first column are set to be zeroes. Another element $S_{N1/2,N2/2}$, which is corresponding to $S_{0,0}$, has to be zero as well. Then, symbols are put onto the odd columns (odd rows) and zeroes are set to the rest even columns (even rows). Since the transmitted optical signals are 2D frames, we can use either odd columns or odd rows to carry symbols. If symbols are on the odd columns, the elements in s have the property that

$$s_{m,n}=-s_{m,N2/2+n}\,.$$

Similarly, if symbols are on the odd rows, the elements in s have the property that

$$s_{m,n}=-s_{N1/2+m,n}\,.$$

In order to obtain the non-negative signals, the negative values in $s_{N1\times N2}$ should be clipped to zeroes because $s_{m,n}$ is real but bipolar. A frame of transmitted signal is given by

$$x_{m,n}=0.5\left(s_{m,n}+\left|s_{m,n}\right|\right)$$

In 2D optical signal transmission, the cyclic prefix (CP) is added to both columns and rows of $x_{m,n}$ to mitigate the effect of misalignment, which is denoted by $\hat{x}_{m,n}$. The intensity of each pixel in the transmitted frame is modulated by a corresponding element in $\hat{x}_{m,n}$. In this paper, we assume that a short range optical path as a flat fading channel so that $\left|h_{m,n}\right|$ is the same for any coordinate point. The noise $w_{m,n}$ consists of shot noise and thermal noise, which can be approximated as additive white Gaussian noise (AWGN). After removing the CP and transforming the arrival signal into the frequency domain, the amplitude of each symbol on the odd columns is reduced by half due to the clipping approach. The symbols appearing on the even columns are clipping noises. The information can be easily recovered by only detecting the symbols on the odd columns.

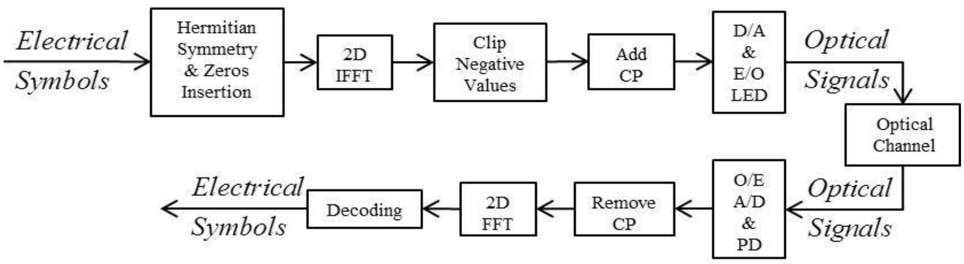

Fig. 1. 2D ACO-OFDM block diagram.

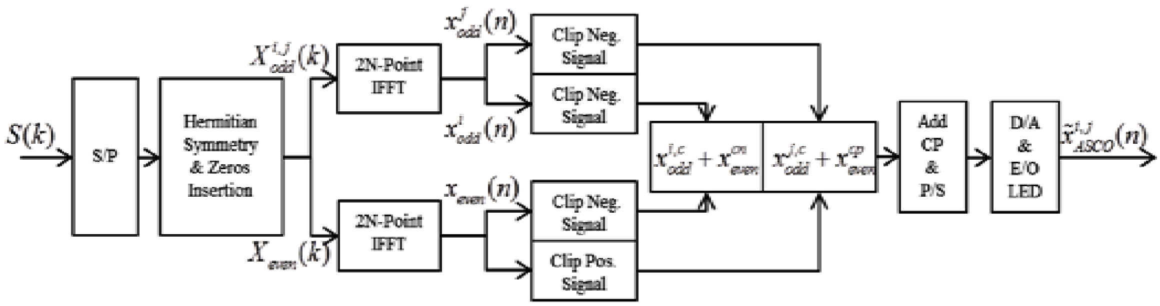

Fig. 2. 2D ASCO-OFDM transmitter block diagram.

B. 2D ASCO-OFDM Transmitter

$$x_{odd}^{j,c}=0.5\left(x_{odd}^{j}+\left|x_{odd}^{j}\right|\right)$$

$$x_{odd}^{i,c}=0.5\left(x_{odd}^{i}+\left|x_{odd}^{i}\right|\right)$$

In this subsection, we describe the block diagram of 2D ASCO-OFDM optical wireless system, which is presented in figure 2. The input symbols are parsed into three parts, then they are mapped into three N1 × N2. Matrices, X^{i}_{odd}, X^{j}_{odd} and X_{even}. The symbols are put onto the odd columns and the even columns respectively. Which are shown as follows:

$$X_{odd} = \begin{bmatrix} 0 & 0 & 0 & . & . & . & 0 & 0 \\ 0 & S_{11} & 0 & . & . & . & 0 & S_{1,N2-1} \\ 0 & S_{21} & 0 & . & . & . & 0 & S_{2,N2-1} \\ . & . & . & . & . & . & . & . \\ 0 & & 0 & . & . & . & 0 & S_{N1-1,N2-1} \end{bmatrix}$$

$$X_{even} = \begin{bmatrix} 0 & 0 & 0 & . & . & . & 0 & 0 \\ 0 & 0 & S_{13} & . & . & . & S_{1,N2-1} & 0 \\ 0 & 0 & S_{23} & . & . & . & S_{2,N2-2} & 0 \\ 0 & 0 & . & . & . & . & . & 0 \\ 0 & 0 & S_{N1-1,3} & . & . & . & S_{N1-2,N2-2} & 0 \end{bmatrix}$$

i and j represent two consecutive time slots. X^{i}_{odd}, X^{j}_{odd} and X_{even} are constraint to 2D Hermitian symmetry, so they can be transformed by a 2D IFFT to obtain real but bipolar matrices x^{i}_{odd}, x^{j}_{odd} and x_{even}. In order to make these matrices real and unipolar, all the negative elements of xi odd and x^{i}_{odd}

They are transmitted in two consecutive sub-blocks, i and j. If an OFDM signal is converted from only even columns, such as X_{even}, the elements in the matrix x_{even} have the property that

$$s_{m,n} = s_{m,N2/2+n}.$$

Thus, half of the information in x_{even} is lost due to clipping. In order to make all the information in x_{even} transmitted, we generate two different clipped signal matrices for x_{even}. Clip the negative elements to zeroes and keep the positive elements, and clip the positive elements to zeroes and turn the sign of negative elements to positive. Then, we have x^{cn}_{even} and x^{cp}_{even}, which are respectively given by

$$x^{cn}_{even} = 0.5\left(x_{even} + \left|x_{even}\right|\right)$$

$$x^{cp}_{even} = 0.5\left(-x_{even} + \left|x_{even}\right|\right)$$

These two signal matrices, x^{cn}_{even} and x^{cp}_{even} will be added to $x^{i,c}_{odd}$ and $x^{j,c}_{odd}$ respectively as follows:

$$x^{i}_{ASCO} = x^{i,c}_{odd} + x^{cn}_{even}$$

$$x^{j}_{ASCO} = x^{j,c}_{odd} + x^{cp}_{even}$$

The transmitted signal x^{i}_{ASCO} and x^{j}_{ASCO} with cyclic prefix (CP) is denoted as $\tilde{x}^{i}_{ASCO}$ and $\tilde{x}^{j}_{ASCO}$. And they are transmitted through the optical channel.

$$Y^{j}_{even} = 0.5\left(\left|\hat{x}^{j}_{odd}\right| - \hat{x}_{even} + \left|\hat{x}_{even}\right|\right)$$

$$Y^{i}_{even} = 0.5\left(\left|\hat{x}^{i}_{odd}\right| + \hat{x}_{even} + \left|\hat{x}_{even}\right|\right)$$

C. 2D ASCO-OFDM Receiver

The ASCO-OFDM receiver is shown in figure 3. Thus, a transmitted ASCO-OFDM signal consists of two parts of signals, x^{i}_{ASCO} and x^{j}_{ASCO}. CPs are attached to x^{i}_{ASCO} and x^{j}_{ASCO} to mitigate the effect of misalignment, which are denoted by $\tilde{x}^{i}_{ASCO}$ and $\tilde{x}^{j}_{ASCO}$. After removing the CP, the arrival signals, y^{i}_{ASCO} and y^{j}_{ASCO}, can be respectively given by

$$y^{i}_{ASCO} = x^{i}_{ASCO}(n) \otimes h(n) + w^{i}(n)$$

$$= (x^{i,c}_{odd} + x^{cn}_{even}) \otimes h(n) + w^{i}(n)$$

$$y^{j}_{ASCO} = x^{j}_{ASCO}(n) \otimes h(n) + w^{j}(n)$$

$$= (x^{j,c}_{odd} + x^{cp}_{even}) \otimes h(n) + w^{j}(n)$$

$$Y^{i}_{odd} = 0.5\hat{x}^{i}_{odd}$$

$$Y^{j}_{odd} = 0.5\hat{x}^{j}_{odd}$$

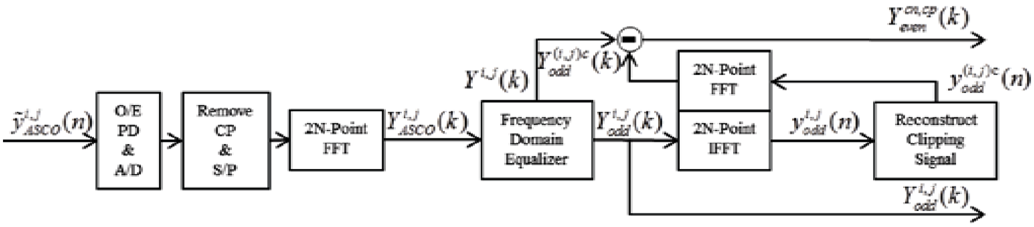

Fig. 3. 2D ASCO-OFDM receiver.

III. CHANEL CAPACITY CALCULATION

Channel capacity of OFDM is defined as the maximum mutual information between input and output of the channel. In optical wireless communication, the information is the optical channel is considered as a flat channel, thus we assume $h(n)$ =1. The combination of all noise $w(n)$ is approximately modeled as additive white Gaussian noise. In order to accurately calculate capacity, cyclic prefix is not considered. Then the channel capacity is given by

$$C = \max I(x, y)$$

Where $I(x, y)$ is the mutual information, which is given by

$$I(x, y) = h(y) - h(w)$$

$$= -\int_{\infty}^{-\infty} f(y)\log_2 f(y)dy - 0.5\log_2 2\pi 2\sigma_n^2$$

$h(y)$ and $h(w)$ are the differential entropy of received signals and Gaussian noise respectively. $f(y)$ is the distribution of transmitted signals plus noise. To calculate the channel capacity of ASCO-OFDM, we derive the distribution of

y^{i}_{ASCO} by convolution the PDF of x^{i}_{ASCO} and Gaussian distribution,

$$f_{y^{i}_{ASCO}}(y)=\int_{\infty}^{-\infty} f_{x^{i}_{ASCO}}(\chi) f(y-\chi)d\chi$$

$$=\frac{\sqrt{2}}{4\pi\sqrt{D+\sigma_n^2}}\exp\left(\frac{-y^2}{2(D+\sigma_n^2)}\right)$$

$$.\int_{\frac{-y\sqrt{D}}{\sigma_n\sqrt{2\left(D+\sigma_n^2\right)}}}^{\infty} \exp(-m^2)$$

$$.\left[erf\left(\frac{\sigma_A\sigma_n m}{\sigma_S\sqrt{D+\sigma_n^2}}+\frac{y\sigma_A\sqrt{2D}}{2\sigma_S(D+\sigma_n^2)}\right)\right]$$

$$+erf\left(\frac{\sigma_s\sigma_n m}{\sigma_A\sqrt{D+\sigma_n^2}}+\frac{y\sigma_s\sqrt{2D}}{2\sigma_A(D+\sigma_n^2)}\right)dm$$

$$+\frac{1}{4\sqrt{2\pi(\sigma_A^2+\sigma_n^2)}}\exp\left(\frac{-y^2}{2\sigma_A^2+\sigma_n^2}\right)$$

$$.\{1-Q(\frac{-y\sigma_A}{\sigma_n\sqrt{2(\sigma_A^2+\sigma_n^2)}})]$$

$$+\frac{1}{4\sqrt{2\pi(\sigma_S^2+\sigma_n^2}}\exp\left(\frac{-y^2}{2(\sigma_S^2+\sigma_n^2)}\right)$$

$$[1-Q(\frac{-y\sigma_S}{\sigma_n\sqrt{2(\sigma_S^2+\sigma_n^2)}})]+\frac{1}{4\sqrt{2\pi\sigma_n}}\exp\left(\frac{-y^2}{2\sigma_n^2}\right)$$

IV. SIMULATION RESULT

In this section, we compare the performances between 2D ASCO-OFDM, 2D ACO-OFDM and ADO-OFDM in terms of Peak-to-average power ratio (PAPR), average bit rate, and symbol error rate (SER). The average optical power of transmitted signals is defined as E{x(n1, n2)}.

A. Peak-to-Average Power Ratio (PAPR)

The intensity of each pixel is plotted against the 2D coordinate n_1 and n_2. The intensity of each pixel is plotted against the 2D coordinate n_1 and n_2. The original symbols are drawn from 4QAM and they are converted by a 2D IFFT into the time domain. Since the output of 2D IFFT follows Gaussian distribution with mean zero and variance σ, the PDF of an ACO- OFDM signal follows clipped Gaussian distribution with mean σ/2π and variance $\sigma^2/2$ The PAPR performances of 2D ASCO-OFDM, 2D ACO-OFDM and 2D ADO-OFDM are compared in figure 4. The red solid curves represent the PAPR of ASCO-OFDM and the black curves represent the PAPR of ACO-OFDM whereas the pink curve represent the PAPR of ADO-OFDM. We can use 4QAM, 16QAM, and 64QAM respectively. For ASCO-OFDM, since ACO-OFDM signals and SCO-OFDM signals are independent, they can be modulated by different constellations. In order to fairly compare the PAPR between two transmitted signals, the same constellation is applied onto odd and even subcarriers for 2D ASCO-OFDM. We notice that the PAPR of 2D ASCO OFDM is 2dB less than that of 2D ACO-OFDM.

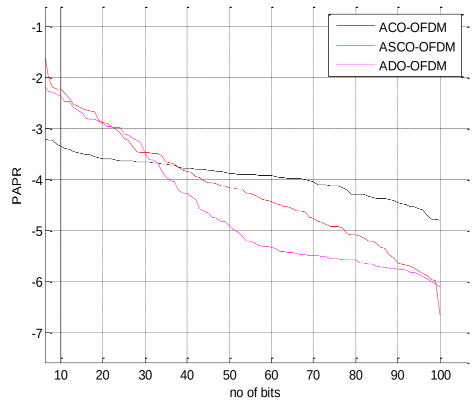

Fig. 4. PAPR (Optical power) comparisons Of 2D ASCO-OFDM, 2D ACO-OFDM and 2D ADO-OFDM.

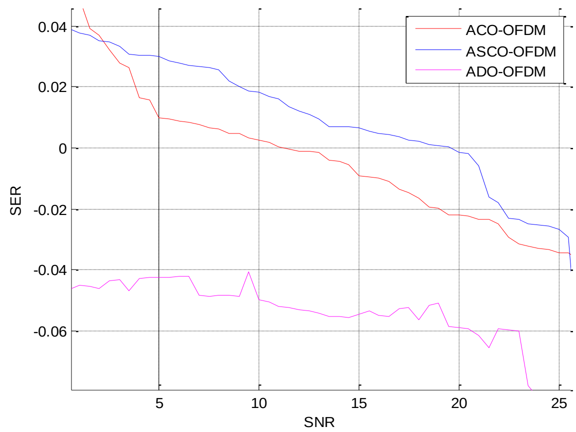

Fig. 5. Ser Comparisons of 2D ASCO-OFDM, 2D ACO-OFDM and 2D ADO-OFDM.

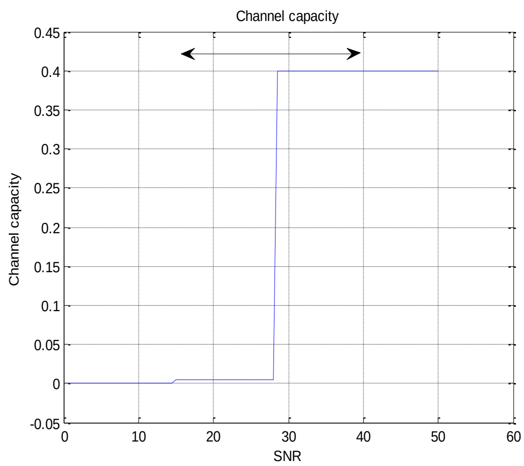

Fig. 6. Channel capacity of 2D ASCO-OFDM.

B. Symbol Error Rate(SER)

The symbol error rate (SER) vs. SNR for 2D ASCO-OFDM and 2D ACO-OFDM in shown in figure 6. The red curve represents 2D ACO-OFDM system and the blue curves represent 2D ASCO-OFDM system.

C. Channel Capacity

The channel capacity ASCO-OFDM is derived. ASCO_OFDM can be used from 0dB SNR case while ACO_OFDM with certain constellation combinations does not work in small SNR cases.

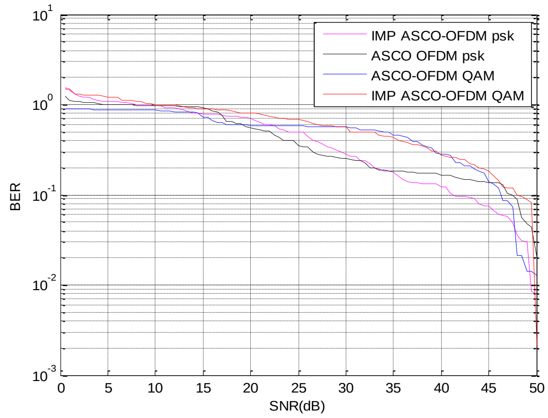

Fig. 7. BER vs SNR comparisons of improved 2D ASCO-OFDM and 2D ACO-OFDM with different constellation combination.

V. Conclusion

Thus in this paper, the ASCO-OFDM scheme is extend into 2D IM/DD optical wireless systems. It improves the spectral efficiency because both odd columns and even columns are used to carry symbols while only odd columns are modulated in the 2D ACO-OFDM scheme. Since the odd columns and the even columns of 2D ASCO-OFDM can be separately detected, different constellation combinations are taken for modulation. By applying smaller constellations, 2D ASCO-OFDM can achieve better SER performance than 2D ACO-OFDM in the same bit rate case. Moreover, the 2D ASCO-OFDM is more power efficient because its PAPR performance is 2dB lower than that of 2D ACO-OFDM. Consequently, ASCO-OFDM is an attractive choice for 2D IM/DD optical wireless systems. The channel capacity is calculated. The channel capacity improvement can be considered as the future scope.

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