Research of adaptive modulation STBC-OCT precoding in MIMO-OFDM VLC system

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Abstract: An efficient precoding scheme combing adaptive modulation, space-time block code (STBC) and orthogonal circulant matrix transform (OCT) is proposed to improve the performance of multiple input-multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) based visible light communication (VLC) systems in this work. A 2×2 MIMO-OFDM VLC system is designed and established to evaluate the performance of the proposed adaptive modulation STBC-OCT precoding scheme. The performances of bit error rate (BER), peak-to-average power ratio (PAPR) are investigated experimentally for different modulation and coding schemes. The performances of BER are studied in different direct current bias (DC) and driving peak-to-peak voltages (V_{PP}) offsets. The experimental results show that the system using proposed adaptive modulated STBC-OCT precoding obtains a relatively flat and higher signal-to-noise ratio (SNR) values, lower PAPR compared with other precoding methods. The proposed scheme can obtain the best BER performance, and it is always lower than the 7% pre-forward error correction (pre-FEC) threshold of $3.8\times10^{-3}$with the transmission distance is 0.5 m, DC is set to 2.7 V and V_{PP} is 2.7-2.8 V, it can effectively overcome the bandwidth limitation of MIMO-OFDM VLC system and provide the best reliability.

Key words: visible light communication; multiple input-multiple output-orthogonal frequency division multiplexing; space-time block code; orthogonal circulant matrix transform; adaptive modulation

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自适应调制 STBC-OCT 预编码在 MIMO-OFDM VLC 系统中的研究

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摘 要：为改善多入多出正交频分复用 (MIMO-OFDM) 的可见光通信 (VLC) 系统的性能,提出将自适应调制、空时分组码 (STBC) 及正交循环矩阵变换 (OCT) 相结合应用于该系统中,设计并建立了一个 2×2 MIMO-OFDM 系统,来评估所提出的自适应调制 STBC-OCT 预编码方案的性能。在不同的调制方式、不同的编码方案下研究其误码率 (BER) 性能、峰均功率比 (PAPR) 性能、不同的直流偏置

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(DC) 与驱动电压峰值 (V_{PP}) 下的 BER 性能。结果表明：与其它预编码方法相比，采用自适应调制 STBC-OCT 预编码方案能获得相对均衡且高的信噪比 (SNR) 值及更低的 PAPR。当传输距离为 0.5 m，DC 为 2.7 V、V_{PP} 为 2.7~2.8 V 时所提方案能获得最佳的 BER 性能，并始终低于前向纠错 (pre-FEC) 门限 7% 的阈值 3.8×10^{-3}。该方案能够有效地克服 MIMO-OFDM VLC 系统带宽限制的问题并提供最佳的可靠性。

关键词：可见光通信； 多入多出-正交频分复用； 空时分组码； 正交循环矩阵变换； 自适应调制

0 Introduction

Visible light communication (VLC) takes the characteristics of rich spectrum resources, security and green energy saving compared with traditional wireless communication, and is a major development trend of future mobile communication wireless network, which can be promoted and applied in smart home, intelligent transportation and wireless access scenarios. VLC is the "last mile" wireless service delivery for its indoor environment, the data rate is limited by the modulation bandwidth of the LED[1−2], which is the main problem, signals modulated at high-frequencies are strongly attenuated by VLC[3], as a result, orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) techniques have been proposed to be combined to form a MIMO-OFDM system. OFDM can overcome the inter-symbol interference (ISI) and improve spectral efficiency great effectively by decomposing the channel into multiple orthogonal sub-channels[4−5], while MIMO can improve the channel capacity and data rate by equipping multiple transmitters and receivers simultaneously[6−7]. Usually, signal-to-noise ratio(SNR) of high-frequency channels is worse than that of the low-frequency channels in VLC system, so an adaptive OFDM modulation scheme is proposed to improve the data rate[8]. The channel matrix correlation of MIMO VLC systems is usually very high, so space-time block code (STBC) is proposed[9−10]. The high peak-to-average power ratio (PAPR) has always been a problem in OFDM signal, orthogonal circulant matrix transform (OCT) is proposed to achieve a relatively flat and higher SNR curve, the bit error rate (BER) performance of the system is improved to suppress the channel multipath fading, high-frequency fading [11−12] and the PAPR [13−14].

The contribution of the paper is to build adaptive modulation STBC-OCT precoding in MIMO-OFDM VLC System. Different from the existed works, it can reduce channel correlation, achieve relatively flat and higher SNR values by using STBC-OCT precoding, make full use of spectrum resources and improve data rate by using adaptive modulation in the system. Finally, a 2×2 MIMO-OFDM VLC system by using the adaptive modulation STBC-OCT precoding is setup, which anti-fading performance, BER performance and PAPR performance of the MIMO-OFDM VLC system without precoding, with STBC precoding, with OCT precoding and with proposed adaptive modulation STBC-OCT precoding is investigated experimentally for different modulation modes, DC bias (DC) and driving peak-to-peak voltages (V_{PP}). The experimental results show that the proposed scheme can obtain the best BER performance compared with other methods, and is always lower than the 7% pre-forward error correction (pre-FEC) threshold of 3.8×10^{-3} with the transmission distance is 0.5 m, DC is 2.7 V and Vpp is 2.7-2.8 V, which can effectively overcome the bandwidth limitation of MIMO-OFDM VLC system and provide the best reliability.

1 Principle

1.1 Adaptive modulation STBC-OCT precoding scheme based on MIMO-OFDM VLC

An efficient adaptive modulation STBC-OCT precoding scheme is proposed due to the problems of high both of channel matrix correlation and PAPR in MIMO-OFDM VLC system, where STBC can robustness to the channel correlation, OCT can reduce the correlation of input sequence by using ZC matrix to suppress high PAPR, and propagate the information on each subchannel to all subchannels to achieve frequency diversity and obtain a relatively flat SNR to improve the BER performance of the system [12].

In order to simplify the analysis and not lose generality, taking two transmitters and two receivers as an example. Figure 1 is the principle block diagram of adaptive modulation STBC-OCT precoding scheme based on MIMO-OFDM VLC system. The principle process is as follows.

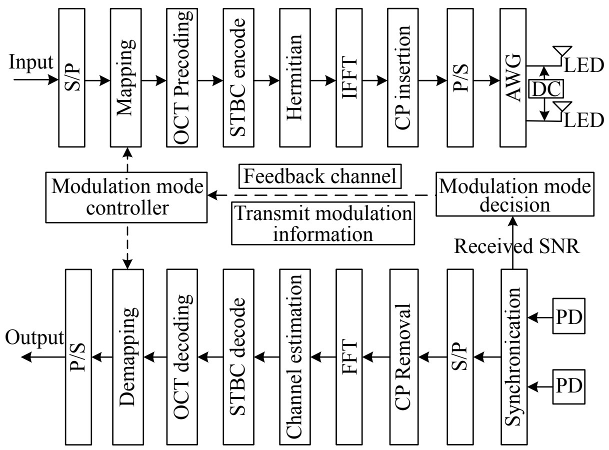

Fig.1 Block diagram of adaptive modulation STBC-OCT precoding scheme based on MIMO-OFDM VLC system

At the transmitter: Firstly the original random binary streams are through serial-to-parallel (S/P) conversion and the modulation mode and constellation mapping at the transmitter are selected adaptively according to the feedback channel, after the OCT precoding and STBC scheme the Hermite transform is performed to ensure that the signals are symmetrical in frequency domain[13]. Secondly, the inverse Fourier transform (IFFT) is used to ensure that the OFDM signals are real-valued in the time domain. The cyclic prefix (CP) is added to the OFDM symbol to overcome ISI, and the transmitted signals are generated which are sent to any signal generator to generate analog OFDM signals after parallel-to-serial (P/S) conversion. Finally, direct current (DC) is added to make the signals non-negative and then sent by two LEDs respectively.

At the receiver: Firstly, two photodetectors receive the optical signal and convert into electrical signal, then the synchronization is used to detect the initial position of each data, channel estimation and noise variance estimation, and calculate the SNR combining with setting BER threshold to get the modulation mode of each subchannel according to the estimation results, and transmitted to the transmitter through the feedback channel. Secondly, the time-domain signals are converted to the frequency-domain signals after serialparallel (S/P) conversion, CP removing and Fourier transform (FFT) operations. Finally, the original binary data stream is recovered by STBC decoding, OCT decoding, demapping and parallel-to-serial (P/S) conversion.

1.2 STBC-OCT precoding principle

In adaptive modulation STBC-OCT precoding, OCT precoding after the constellation mapping, where redistributes the noise on each subchannel to each subcarrier, so that the SNR value of each OFDM symbol is uniform.The circulant matrix is generated by ZC sequence, which has ideal periodic autocorrelation and low cross-correlation, so that the circulant matrix constructed has orthogonality. ZC sequence is defined as[15−16]:

$$Z(k)=\begin{cases} e^{-j\pi un(n+2q)/N} & N \text{ is even number} \\ e^{-j\pi un(n+1+2q)/N} & N \text{ is odd number} \end{cases} \tag{1}$$

Where $k=0,1,\ldots,N-1, 0\leqslant n<N$, $0<u<N$, N and u are prime numbers to each other, q is natural numbers, and N is the length of the sequence, which is the same as the number of subcarriers in a single symbol.

OFDM symbol after mapping can be expressed as: $X=[X_1,X_2,\cdots X_N], 1\leqslant i\leqslant N$.

The above X_i formula represents the subcarriers in each frequency domain and N is the number of subcarriers in OFDM symbol. Then, the mapped subcarriers are precoded by OCT, that is, multiplied by the orthogonal circulant matrix Z generated by ZC sequence[14]:

$$S=X\times Z=\frac{1}{\sqrt{N}}[X_1,X_2,\cdots X_N]\times\begin{bmatrix} Z_1 & Z_2 & \cdots & Z_N \\ Z_N & Z_1 & \cdots & Z_{N-1} \\ \vdots & \vdots & \cdots & \vdots \\ Z_2 & Z_3 & \cdots & Z_1 \end{bmatrix} \tag{2}$$

Where $\frac{1}{\sqrt{N}}$ is to normalize the transmission power, the signal S after OCT precoding is encoded by STBC encoder[17]:

$$SS = \begin{bmatrix} S_1 & -S_2^* \\ S_2 & S_1^* \end{bmatrix} \tag{3}$$

Where $*$ denotes conjugate operation.

At the receiver, after CP removing and Fourier transform (FFT) operations the received signal is expressed as:

$$Y = \eta H(t) SS(t) + N(t) \tag{4}$$

Where η is the photoelectric conversion efficiency, $N(t)$ is the additive Gaussian white noise matrix, its mean-value is zero, $H(t)$ is the channel response matrix at t^{th} time.

1.3 Adaptive modulation scheme

The *BER* performance of the system is poor due to the high frequency channel attenuation in VLC system, so an adaptive modulation scheme is proposed. The basic thought is to calculate the SNR according to the result of noise variance estimation at the receiver, and then to get the maximum value of modulation mode and order of each sub-channel combined with the set *BER* threshold, and finally to feed back to the transmitter. Therefore, the low-order modulation with larger attenuation and high-order modulation with smaller attenuation on the subcarriers is adopted, which can make full use of the spectrum resources and improve the data rate.

So, the received *SNR* of the signal on the k^{th} subchannel is[12,18]:

$$SNR(k) = \frac{1}{\sigma^2(k) Z_n^H \left[\left(\|H_0\|_F^2 \right)^{-1} \left(\|H_1\|_F^2 \right)^{-1} \cdots \left(\|H_{N-1}\|_F^2 \right)^{-1} \right]^{\mathrm{T}}} \tag{5}$$

Where the transmit power has been normalized, $0 \leqslant k < N$, $\sigma^2(k)$ represents the noise power of the k^{th} subchannel, Z_n^H is the n^{th} row of the Z^H, $\|\cdot\|_F$ is the Frobenius 2-norm , and H_i is the channel matrix of the i^{th} subchannel.

Taking QAM as an example, the relationship between *BER*, *SNR* and modulation order is as follow[19]:

$$BER \leqslant 0.2 \exp\left(-1.5 \frac{SNR(k)}{P-1} \right) \tag{6}$$

In equation (6), if BER_0 is given, the modulation order of the k^{th} subchannel in the transmitted signal is obtained from equation (7):

$$\left\lfloor P(k) = 1 - \frac{1.5\, SNR(k)}{\log(5\, BER_0)} \right\rfloor \tag{7}$$

Where $\lfloor \cdot \rfloor$ means rounding down, because the modulation order an integer and an exponent of 2 generally, and the actual *BER* less than the set BER_0. The optimal modulation order is determined by equation (7).

1.4 PAPR performance

After OFDM, the time domain signal on the k^{th} subchannel of the i^{th} transmitter is expressed as[12]:

$$F_{i,k} = \frac{1}{\sqrt{M}} \sum_{n=0}^{M-1} SS_{i,n} \mathrm{e}^{j\frac{2\pi nk}{M}} \tag{8}$$

Where $n = 0, 1, 2, \cdots, M-1$, $i = 1, 2$ is the transmitter index, and M is the number of subcarriers, $SS_{i,n}$ indicate the signal of the i^{th} transmitter after STBC coding.

The *PAPR* of OFDM signal can be expressed as[12]:

$$PAPR = \frac{\max\left[\left| F_{i,k} \right|^2 \right]}{E\left[\left| F_{i,k} \right|^2 \right]} \tag{9}$$

In equation (9), the unit of *PAPR* is dB, which $E[.]$ is the expectation operation. It can be seen that the sum of the signal on each subchannel is multiplied by the rotation factor, and the energy are redistributed by precoding, which leads to the decrease the correlation of input and high *PAPR* in OFDM.

The higher *PAPR*, the higher the probability of LED nonlinear distortion, and the worse *BER* performance of the system. The complementary cumulative distribution function (CCDF) is used to evaluate the performance of *PAPR*, it represents the probability that the *PAPR* of OFDM symbol exceeds the given threshold $PAPR_0$:

$$CCDF = Prob\,(PAPR > PAPR_0) \tag{10}$$

2 Experimental setup and result analysis

The experimental setup of a 2×2 MIMO-OFDM VLC system is shown in Fig.2. At the transmitter, the generated signals are uploaded into an arbitrary function generator. DC offffset is also supplied by signal generator to ensure the positivity of the transmitted signals. Then, mixed signals are transmitted by two LEDs. At the receiver, the optical signals are converted into electrical signals by two photodetectors (PDs), which are recorded by a high-speed digital oscilloscope. The parameters used in the experiment are shown in Table 1.

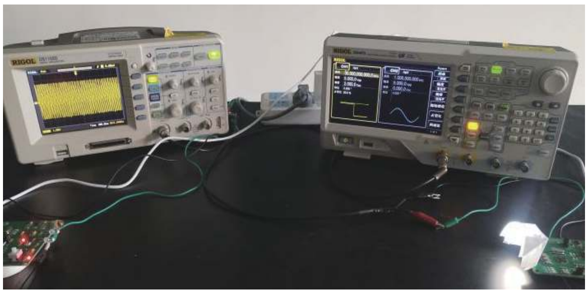

Fig.2 Experimental setup of the proposed MIMO-OFDM VLC system

Tab.1 Experimental parameters

System parameters	Values
Modulation order	8 QAM、16 QAM、64 QAM
Bandwidth/MHz	12.5
FFT length	1 024
Subcarrier number	256
CP length	16
Transmission distance/m	0.5
Distance between TXs/cm	7
Distance between RXs/cm	10

Figure 3 shows the BER curves of BPSK, QPSK, 8 QAM, 16 QAM and 64 QAM modulation respectively. The BER of the five modulation methods is gradually decreasing with the increase of SNR; SNR required for PSK modulation is smaller at the same BER level compared with QAM modulation; the BER of the system is also increasing with the increase of QAM modulation order; when *BER* is at the 7% pre-forward error correction (pre-FEC) threshold of 3.8×10^{-3}, the *SNR* required for BPSK, QPSK, 8 QAM, 16 QAM and 64 QAM modulation are 3.8 dB, 7 dB, 9.6 dB, 13 dB and 20.7 dB; according to estimate of the *SNR* on the receiver, the modulation mode of the transmitter can be adaptively selected through the feedback channel, BPSK, QPSK or 8 QAM modulation is adopted if the *SNR* is small, otherwise 16 QAM or 64 QAM modulation. Under the same BER, it can greatly improve the utilization of frequency band adaptive modulation method compared with a certain fixed modulation method is used.

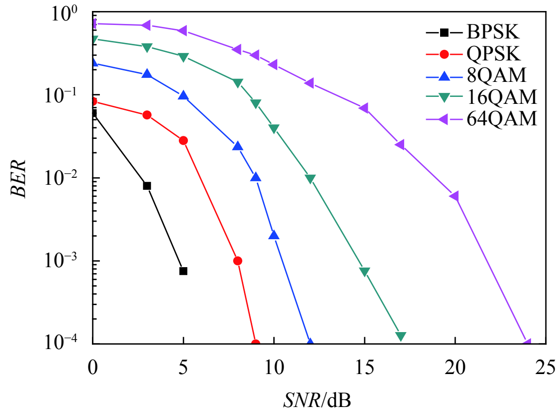

Fig.3 BER curve of adaptive modulation

Figure 4 shows the curves of the *SNR* with the subcarrier index in the traditional MIMO-OFDM system, STBC coding, OCT precoding and STBC-OCT precoding. In the traditional MIMO-OFDM, the *SNR* is reduced from 22 dB to 8 dB, and the higher-frequency fading is obvious, which is mainly caused by the nonlinear characteristics of the LED; the SNR of a single STBC code is reduced from 27 dB to 12 dB, and the average SNR is about 4 dB higher than that of traditional MIMO-OFDM. Therefore, it is beneficial for higher-frequency fading. However, the system using a single STBC code is still limited by bandwidth, and its *SNR* curve drops monotonously; a single OCT precoding has a *SNR* curve of about 14 dB within the subcarrier index range; STBC-OCT precoding still maintains the relatively flat *SNR*

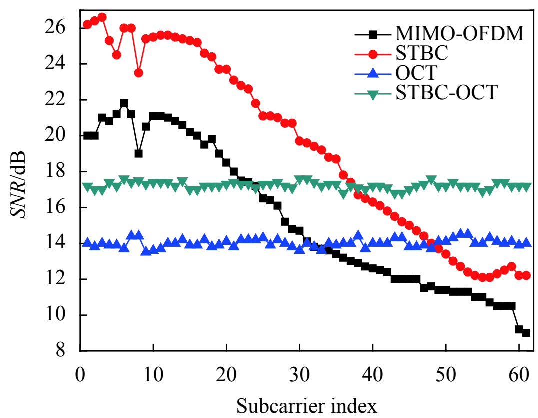

Fig.4 SNR curves of different schemes of MIMO-OFDM VLC system

advantage of a single OCT precoding, and the *SNR* is increased by about 3 dB compared with OCT precoding, so it can effectively overcome the problem of bandwidth limitation in MIMO-OFDM VLC system.

Figure 5 shows the simulation results of the CCDF curves of the traditional MIMO-OFDM system, STBC coding, OCT precoding and STBC-OCT precoding schemes. The *PAPR* performance is similar to the MIMO-OFDM system, STBC coding and OCT precoding, while the *PAPR* of the STBC-OCT precoding system is much lower. At the $CCDF=10^{-4}$, the STBC-OCT precoding scheme was used to obtain a gain of 2 dB over the *PAPR* of the other three schemes.

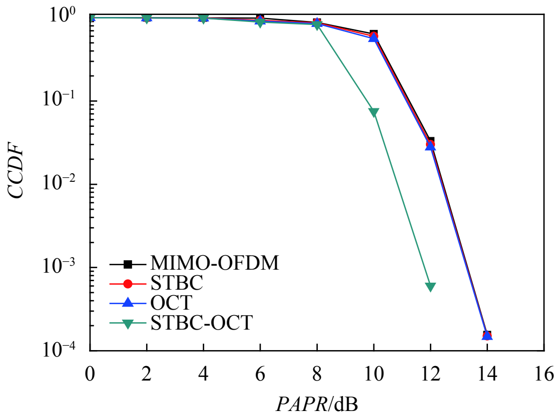

Fig.5 CCDF curves of different PAPR schemes of MIMO-OFDM VLC system

BER is an important indicator to measure system performance, so the relationship between *BER* performance of MIMO-OFDM VLC system and driving peak voltage (V_{pp}) and direct current offset (DC) is further analyzed.

Figure 6 shows the *BER* of the traditional MIMO-OFDM, OCT precoding and STBC-OCT precoding schemes under different DC bias conditions. Using Rebel Star 01 LED, the LED's starting light-emitting voltage is 2.2 V through experimental tests, and the LED has a good linearity in the range of 2.5 V to 2.9 V[14−15]. In the experiment, V_{pp} is set to 2.8 V, and the DC bias is 2.4-3.1 V, the *BER* of each curve shows a trend of first decreasing and then increasing with the DC bias increases. When the DC is 2.7 V, this value is exactly in the middle of the linear voltage region of the LED, so the error performance of the three curves is the best, and the *BER* are 5.45×10^{-1}, 2.3×10^{-1}, 8.8×10^{4}. The STBC-OCT precoding has the best *BER* performance and is always lower than the 7% pre-FEC threshold of 3.8×10^{-3}, which is mainly due to the flatness of the *SNR*, which reduces the higer-frequency attenuation error, thereby improving the *BER* performance of the system.

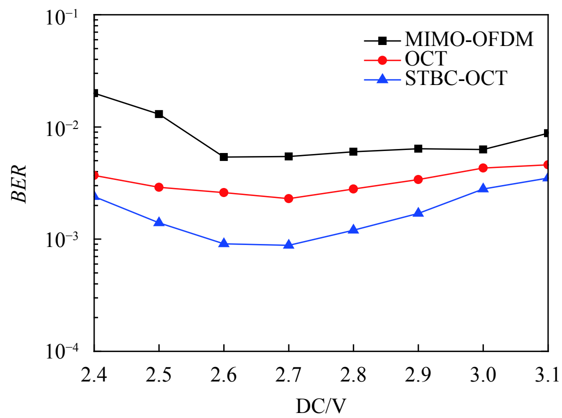

Fig.6 BER curves of different schemes of MIMO-OFDM VLC system at different DC

In addition, in the experiment, the DC offset is set to 2.7 V, and the V_{pp}-value is from 2.1 V to 3.3 V, the *BER* performance of different schemes is shown in Fig.7. The *BER* of each curve also shows a trend of first decreasing and then increasing with the increase of V_{pp}, When V_{pp}= 2.7 V, the *BER* of STBC-OCT precoding is 1×10^{-3}, V_{pp}=3.1 V, the *BER* of MIMO-OFDM and OCT preco-

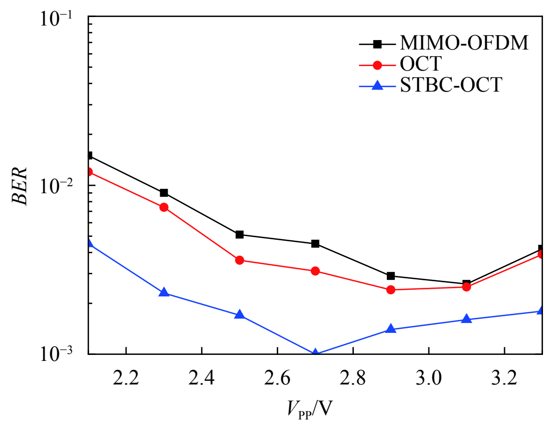

Fig.7 BER curves of different schemes of MIMO-OFDM VLC system at different V_{pp}

ding are 2.6×10^{-3}, 2.5×10^{-3}, the STBC-OCT precoding performance is the best and it is lower than the 7% pre-FEC threshold of 3.8×10^{-3}. Experimental results show that the *BER* decreases first with the increase of V_{pp}, because increasing V_{pp} can improve the *SNR*, Then the *BER* increases again, and when V_{pp} continues to increase, nonlinear distortion plays a leading role.

3 Conclusions

In this paper, an adaptive modulation STBC-OCT precoding scheme based on the MIMO-OFDM VLC system is proposed. The BER performance and PAPR performance of the MIMO-OFDM VLC system without precoding, with STBC precoding, with OCT precoding and with proposed adaptive modulation STBC-OCT precoding is investigated experimentally for different modulation modes, DC bias and driving peak-to-peak voltages (V_{PP}). The experimental results show that by using adaptive modulation STBC-OCT precoding the uniform, high SNR value and a lower *PAPR* value is achieved over data subcarriers for the MIMO-OFDM VLC system compared with other existing schemes, which can effectively overcome the problem of bandwidth limitation of MIMO-OFDM VLC systems. Therefore, when the sample rate of AWG is 100 MS/s, transmission distance is 0.5 m, DC is 2.7 V, V_{pp} is 2.7-2.8 V, the *BER* performance using proposed scheme can be reduced to 8.8×10^{-4}, which achieves better *BER* performance than other existing schemes, and below the *BER* threshold of 7% FEC. In summary, the proposed adaptive STBC-OCT precoding can be considered as a potential and suitable candidate for MIMO-OFDM VLC systems, which can significantly improve the reliability of the system.

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