Carrier allocation combined with independent component analysis for multiple-input-multiple-output visible light communication

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1 Introduction

Visible light communication (VLC) system will be required to be capable of supporting up to hundreds of megabits per second or even multigigabit high-speed packet data transmission in the future. Multiple-input–multiple-output (MIMO) can make full use of space resources, maximizing spectrum utilization, and power efficiency. So, MIMO wireless transmission technology is the key to the future VLC. MIMO indoor VLC system, transmitting signals through multilight sources, has higher capacity and transmission rate than the single input-single output (SISO) system. On the one hand, MIMO indoor VLC can meet the lighting requirements. On the other hand, it can overcome the shadow effect in communication system and increase the communication distance.

In MIMO VLC system, the channel is divided into various separate subchannels. Multiple users modulation, precoding, and adaptive equalization techniques are often employed to overcome the mutual interference between each subchannel. All of the above work is based on the channel state information (CSI) under the predictable premise. However, in the actual case, to accurately estimate the channel information is almost impossible. Also, the estimation of the channel itself will introduce large error so that the bit error rate is almost impossible. Also, the estimation of the channel information (CSI) under the predictable premise. However, in the actual case, to accurately estimate the channel information is almost impossible. Therefore, this paper proposes an MIMO VLC system scheme in which precoding subcarrier allocation modulation is employed at transmitters and through the independent component analysis (ICA) algorithm separation mixed signals at receiver. This scheme improves the independence of each modulated signals and do not rely on the channel estimation.

2 MIMO Indoor VLC Model

In indoor VLC system, a typical MIMO VLC system can be expressed as the model shown in Fig. 1. When every light-emitting diode (LED) source sends signal at the same time, the received signals at receiver comprise signals received directly and reflected optical signals, for the reason of multipath transmission of light. The solid arrows indicate the direct transmission path, whereas the dotted arrows indicate the reflection path. The total number of LED light sources and different direction receiving antennas are assumed to be K and L, respectively, in this system.

Because every LED light reaches the receiving end through different path and a single LED light can also have multiple transmission paths, the multipath effect of visible light signal transmission is obviously. Therefore, a single LED light signal transmission process in this communication system can be expressed as

\[ R(n) = X(n) + \sum_{i=1}^{N} a_i X(n-t_i) + N(n), \quad i = 1, 2, \ldots, N, \]

(1)
and take a lot of time. From Eqs. (2) and (3), we can see the process of channel estimation will generate large error.

Studies are based on the estimation of channel sources) transmit simultaneously and Eq. (1) can be regarded as the case of one LED light path in this system. When the K sources transmit signals simultaneously, the K receiving antennas would receive the mixed signals from the K sources. So, in this case, the system can be expressed in the matrix form, as Eqs. (2) or (3):

\[ R = HX + N, \]

where \( R(n), Y(n), a_i, t_i, \) and \( N(n) \) represent the LED transmission signal, the received signal, the coefficients, the delay time, and Gaussian background noise, respectively. \( N \) is the reflecting times of the received signal, researches show that the three times reflected signal is negligible. Therefore, we take \( N = 2, a_i \) is the strength coefficient of the reflection delay signal and \( 0 < a_i < 1 \).

Figure 1 shows the system of \( K \) LED light sources (signal sources) transmit simultaneously and Eq. (1) can be regarded as the case of one LED light path in this system. When the \( K \) sources transmit signals simultaneously, the \( K \) receiving antennas would receive the mixed signals from the \( K \) sources. So, in this case, the system can be expressed in the matrix form, as Eqs. (2) or (3):

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equivalent to

\[ \begin{pmatrix} r_1 \\ \vdots \\ r_K \end{pmatrix} = \begin{pmatrix} h_{11} & \cdots & h_{1K} \\ \vdots & \ddots & \vdots \\ h_{K1} & \cdots & h_{KK} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_K \end{pmatrix} + \begin{pmatrix} n_1 \\ \vdots \\ n_K \end{pmatrix}, \]

where \( R, H, X, \) and \( N \) in Eq. (2) denotes the received signal matrix, the channel matrix, source signal matrix, and Gaussian noise matrix, respectively. In Eq. (3), \( r_i \) is the signal received by the \( i \)'th receiving antenna, \( x_j \) is the \( i \)'th source transmitted signal, \( h_{ij} \) denotes the channel between the \( i \)'th transmitting antenna and the \( j \)'th receiving antenna, and \( n_i \) is the Gaussian noise.

In order to recover \( X \) from the received signal \( R \), previous studies are based on the estimation of channel \( H \). But, the process of channel estimation will generate large error and take a lot of time. From Eqs. (2) and (3), we can see that this signal process have the same form with ICA signal process. So, we can restore the source signals by ICA algorithm when the source signals satisfy the independent principle. The ICA algorithm is to find a separation matrix \( W^T \) to separate the received signal. The details are as follows:

\[ Y = W^TR = W^THX + W^TN. \]

Let \( E = W^TH, Z = W^TN \) in Eq. (4), so

\[ Y = EX + Z, \]

where \( Y \) is the restored signal and \( E = W^TH, Z = W^TN \). The ICA algorithm is designed to make \( E \) tend to a unit matrix and \( Z \) tend to a zero matrix, thus

\[ Y = X + Z. \]

3 System Design

This section proposes the MIMO VLC scheme which is based on the precoding carrier allocation and ICA algorithm. At the sending end, the preprocessed data are sent into modulators separately and modulated by different carriers. At the receiving end, ICA algorithm is used to separate the mixed-signal and demodulate without CSI.

3.1 Precoding Carrier Allocation Modulation

ICA is based on the basic principle of statistical independence, which is the key to achieve the ICA algorithm. In practice, the independence between variables in ICA algorithm is often measured by non-Gauss difference, nonlinear irrelevance, and mutual information.

The modulated signals have a strong correlation and small non-Gauss difference in traditional MIMO VLC system whose carrier frequencies are the same. Therefore, traditional MIMO VLC scheme is not conducive to apply ICA algorithm to separate the mixed signals. Based on this, we propose the carrier allocation modulation to strengthen the independence between each modulated signal. The intensity modulation and direct detection (IM/DD) method is well adopted to achieve the VLC, so we need not worry about the problem of limited bandwidth. Meanwhile, in order to restore the phase of source signal, add prefix “1” as the phase identification to bytes allocated data. The block diagram of the sending end is shown in Fig. 2.

We know that the independence between two signals is the basic principle to achieve the ICA algorithm, and in this paper, nonlinear irrelevance is adopted to measure the independence of signals. Random variable \( X \) is nonlinear irrelevant to \( Y \) when their arbitrary continuous function meet the relationship shown in Eq. (7), it is concluded that \( X \) and \( Y \) are mutually independent.

\[ Z = W^TX; \]

\[ E = W^TH; \]

\[ Y = X + Z. \]

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\[ Y = X + Z. \]
In order to make the ICA algorithm work effective in separating the mixed modulated signals, we hope that the modulated signals meet the nonlinear irrelevance which is shown above at the sending end. When phase-shift-keying (2PSK) modulation is applied in this MIMO visible communication system, the modulated signal at the n'th sending end can be expressed as
\[
\cos(2\pi f_n t + s_n),
\]
where \(f_n\) is the carrier frequency and \(s_n\) is the phase dependent on the modulating signal. It is easy to prove that the modulated signals would meet the nonlinear irrelevance criterion expressed by Eq. (8) when the carrier frequency at each sending end is allocated by Eq. (10) and a reasonable setting of \(i\) and \(j\). Therefore, when the carriers are allocated by Eq. (10), the modulated signals meet the independence principle and the requirement of ICA algorithm is met
\[
f_n = n \cdot f_1, \quad n = 1, 2, \ldots.
\]

In a practical system, we add prefix “1” to the paralleled data to produce the preprocessed data. As Fig. 2 shows, binary-PSK (BPSK) modulation based on the carrier allocation is used to modulate the preprocessed data at the sending end. Let \(f_2 = f_1 + \Delta f\), Fig. 3 shows the correlation coefficient between two modulated signals vary with \(\Delta f\).

In Fig. 3, the abscissa from 0 to 500 means the \(\Delta f\) ranging from 0 times \(f_1\) to 5 times \(f_1\). As shown in Fig. 3, when the frequency difference \(\Delta f\) is 0 \((f_2 = f_1)\), the two modulated signals have the strongest correlation. With frequency difference increasing, the correlation coefficient shows a decreasing trend, and the correlation coefficient close to 0 when \(f_2 \geq 2f_1\). When \(\Delta f = n \cdot f_1, \ n = 1, 2, \ldots\), the correlation coefficient between two modulated signals is 0. Further, nonlinear irrelevance is adopted to measure the independence of signals in ICA algorithm, and then we can use the nonlinear irrelevance to measure the independence of signals. Therefore, when the carriers are allocated according to Eq. (10), the modulated signals are independent of each other and meet the independence principle of ICA algorithm. So, the carrier allocation modulation can reduce the correlation between each modulated signal and improve the separation performance of received mixed signal in ICA algorithm. In fact, the carrier allocation modulation can also reduce the intercell interference of MIMO VLC.

### 3.2 Use ICA to Separate the Received Signals

The modulated signals \(X\) turn into the observed signals (received signals) \(R\) at the receiving end after being transmitted through the wireless channel, \(R\) is the mixing of \(X\). Because the modulated signals \(X\) modulated by the proposed carrier allocation modulation are independent of each other, we can use ICA algorithm to separate the observed signal without estimating the CSI to get the separated signal \(Y\). In this paper, FastICA algorithm is applied. FastICA algorithm is designed to find a direction to make \(W^T R = W^{T1} R\) has the maximum non-Gaussian. Non-Gaussian can be measured by entropy which is shown below:
\[
N_g(Y) = \{E[g(Y)] - E[g(Y_{Gauss})]\}^2,
\]
where \(Y_{Gauss}\) is the Gauss random and \(Y_{Gauss}\) has the same variance with \(Y\), \(H(\cdot)\) represents the differential entropy of random variable.

In order to derive the FastICA algorithm, we must first ensure that the maximum approximation of negative entropy of \(W^T R\) can be obtained by optimizing \(E\{G(W^T R)\}\). According to Kuh-Tucker, under the constraint of \(E\{(W^T R)^2\} = ||W||^2 = 1\), the optimal value of \(E\{G(W^T R)\}\) can be obtained on the condition of
\[
E\{Rg(W^T R)\} + \beta W = 0,
\]
where \(\beta = E\{W_0^T R g(W_0^T R)\}\) is a constant value, \(W_0\) is the optimization value of \(W\). We use Newton iteration to solve Eq. (12). Let \(F\) denote the left part of Eq. (12), we can obtain the Jacobian matrix \(JF(W)\) as
\[
JF(W) = E\{RR^T g'(W^T R)\} - \beta I.
\]
And then
\[
E\{RR^T g'(W^T R)\} \approx E\{RR^T\} \cdot E\{g'(W^T R)\} \approx E\{g'(W^T R)\} I.
\]
\[ W^* = W - \frac{1}{2} E\{Rg(W^T R)\} - \beta W, \quad W = W^*/\|W^*\|, \]

(16)

where \( W^* \) is the new value of \( W \), \( \beta = E\{W^T Rg(W^T R)\} \).
Normalization can improve the stability of solution, after simplifying it we can obtain the iterative formula of FastICA algorithm as

\[ W^* = E\{Rg(W^T R)\} - E\{g(W^T R)\} W, \quad W = W^*/\|W^*\|. \]

(17)

So, the iterative algorithm shown in Eq. (17) can find a \( W^T \) such that \( R \) has the maximum non-Gaussian, and the treated \( Y \) is the restored signal of \( X \).

4 System Simulation

In order to verify the feasibility of the proposed scheme, the simulation experiments are implemented as follows. In the simulation, precoded and carrier allocation modulation are adopted at the sending end, and ICA algorithm is applied to separate the observed mixing signal at the receiving end. At the same time, carriers of the same frequency are used to modulate the signals as a comparison with the proposed modulation scheme. Because of the Rayleigh fading characteristic of the VLC channel, the Rayleigh fading channel is assumed in the simulation.11

In the simulation, there are four sending and receiving nodes assumed in the MIMO VLC system, that is \( K = 4, L = 4 \). The modulated signals are sent into the channel and superposed with signal-to-noise ratio(SNR) = 20 dB white Gauss noise. Using ICA algorithm to separate the mixed signal received from the four receiving nodes. Figure 4 shows the simulation process of the proposed communication scheme based on the carrier allocation combined with ICA. As a contrast, Fig. 5 shows the simulation process of the communication scheme based on the same frequency carrier-based modulation combined with ICA.

In Fig. 4, the first part shows the four modulated signals based on the carrier allocation 2PSK modulation, and the mixed signals are shown in the second part, whereas the restored signals are shown in the third part. In Fig. 5, the first part shows the four modulated signals based on the same frequency carrier 2PSK modulation, and the mixed signals are shown in the second part, whereas the restored signals are shown in the third part. The modulated signals based on the carrier allocation modulation are independent of each other and meet the independence principle of ICA algorithm. Although the same frequency carrier modulation based modulated signals have strong correlation, and they do not satisfy the independence principle of ICA algorithm. So, as shown in Fig. 4(c), the proposed MIMO VLC scheme can restore the modulated signals at the receiving end for just change the phase and amplitude of the source signal. By comparison, Fig. 5(c) shows that the comparison scheme cannot restore the modulated signals.

Because of each sending end with a different carrier frequency, we can distinguish the various restored signals.
Precoding data can find the change of phase amplitude. Based on this, the proposed MIMO VCL scheme based on the carrier allocation and ICA can be effectively implemented in the unknown CSI case.

5 Analysis of System Performance

The modulated signals modulated by carrier allocation based 2PSK modulation at the sending end solved the independence requirement of ICA algorithm, makes it possible to use ICA algorithm in MIMO VLC systems without CSI. In order to verify the performance of the proposed MIMO VLC scheme, 2PSK and $2 \times 2$ MIMO VLC system are adopted to investigate the SNR and bit error ratio (BER) performance. The effect of the proposed system on the SNR and BER of the restored signal is studied and compared with the detection method based on the channel estimation.

5.1 SNR Performance of the Proposed System Scheme

Because the degree of non-Gaussian is measured by high-order cumulant and the high-order cumulant of Gaussian random variable is 0, ICA algorithm can theoretically remove Gaussian noise. Therefore, we expect that the separated signals have a higher SNR than the received signal. The effect of signal separation process on the SNR is shown in Table 1.

Where $R_s$ represents the SNR of the received signal, $D_s$ represents the SNR of the separated signal, the separated signal is restored from the received signal by ICA algorithm. As shown in Table 1, the SNR of the separated signal improved when the SNR of the received signal is low. Although the received signal at higher SNR, the SNR of the separated signal is decreased a little. Therefore, the proposed scheme can improve system performance at low SNR environment, and also close to the ideal requirement at high SNR environment.

5.2 BER Performance of the Proposed System Scheme

In order to study the BER performance of the proposed communication scheme, $2 \times 2$ MIMO VLC system is adopted as the simulation system. 2PSK modulation based on the carrier allocation is used in each sending end. ICA algorithm is used to restore modulated signal from the received signal, whereas MMSE and ZF are the comparison schemes under the same conditions to restore the modulated signal. The BER of each scheme is shown in Fig. 6, the abscissa represents the SNR of the received signal.

In Fig. 6, the black line represents the theoretical BER of 2PSK modulation in SISO VLC system and the other three curves represent the BER of the above three signal processing schemes, respectively, in $2 \times 2$ MIMO VLC system. When the SNR $\leq 0$ dB, the BER of the proposed scheme

<table>
<thead>
<tr>
<th>$R_s$ (dB)</th>
<th>$-6$</th>
<th>$-4$</th>
<th>$-2$</th>
<th>$0$</th>
<th>$2$</th>
<th>$4$</th>
<th>$6$</th>
<th>$8$</th>
<th>$10$</th>
<th>$12$</th>
<th>$14$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s$ (dB)</td>
<td>$-2.7$</td>
<td>$-2.4$</td>
<td>$-1.1$</td>
<td>$0.04$</td>
<td>$1.9$</td>
<td>$3.2$</td>
<td>$4.5$</td>
<td>$6.2$</td>
<td>$7.5$</td>
<td>$8.7$</td>
<td>$9.7$</td>
</tr>
</tbody>
</table>
is slightly lower than the two comparison schemes, and all of them are close to theoretical BER of the 2PSK modulation. With the SNR increasing, the BER of the proposed scheme decreases significantly, and its BER reaches the level of one millionth when SNR = 14 dB. In contrast, the BER of the MMSE and ZF based scheme which dependent on CSI estimation greater than 0.00001 under SNR = 14 dB and decrease slowly with the increasing SNR. So, the proposed communication scheme has a better BER performance than the method based on CSI estimate like MMSE or ZF.

6 Conclusion

It is difficult to precisely estimate the channel in practical MIMO VLC system. Sometimes there is no CSI available at all. Under such conditions, those CSI-based algorithms would not work or work with poor efficiency. In this paper, we propose an indoor MIMO VLC scheme based precoding carrier allocation and ICA. Carrier allocation ensures that the modulated signals are independent of each other such that the application of ICA to separate the mixed modulated signal is possible. Simulation results show that the proposed MIMO VLC scheme can be implemented successfully without CSI, and both SNR performance and BER performance have reached a good level.

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References


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