Implementation and decoding method of OCC system based on MIMO*

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(Received 10 June 2021; Revised 15 August 2021)

The application of high-frame-rate cameras as well as the complex image processing techniques will lead to a series of problems, such as high system cost and long transmission delay. In this paper, we introduce narrow-band filtering technology to reduce the impact of optical noise and reduce the complexity of image processing from the physical level. We also introduce multiple-input multiple-output (MIMO) technology into the optical camera communication (OCC) system to increase system transmission rate, and propose a light emitting diode (LED) array decoding algorithm based on the directional projection method to reduce the system delay. By accumulating the target pixel values in each row and column of the image, the proposed method then determines the position and boundary of the detected target to distinguish the target area from the background. Experimental results indicate that the communication distance can reach up to 5.5 m without error bits detected. When the LED array at the transmitter of this system flashes at a frequency of 12 Hz, the transmission rate can reach 126.32 bit/s.
Document code: A **Article ID:** 1673-1905(2022)01-0018-6
DOI https://doi.org/10.1007/s11801-022-1093-y

Optical camera communication (OCC) is a visible light communication (VLC) technology that uses image sensor (IS) as the receiver to receive light signals[1]. Photodiode (PD) and IS are two common types of receivers in VLC field[2]. Although using PD can achieve a high data rate in the communication system, its characteristic of susceptible to interference from sunlight and other light emitting diode (LED) light sources limits its application in outdoor scenarios, e.g., the intelligent transportation system (ITS). IS, with its advantage of wide field of view (FOV) and multiple-input multiple-output (MIMO) ability, shows great potential in ITS field. By converting the received optical signal into a digital image through IS image processing technology, reducing the impact of various optical noises in the system, and obtaining a higher signal-to-noise ratio gain. Thus, IS can help to achieve a high performance communication system[3].

In the existing research, the OCC system mostly uses a single LED with a large diameter as the transmitting device and the high frame rate camera as a receiving device. High frame rate cameras are not suitable for car cameras due to their high cost and LEDs with larger diameters are not suitable for actual OCC scenarios. In most studies, complex image processing techniques are used to eliminate noise, but the processing overhead is large, which brings the information transmission delay. Use 4×5 LED array as transmitter, no error at communication distance of 1.5 m[4]. Use 4×4 LED array as transmitter and static high-speed camera with frame rate of 435 fps as receiver, no error at communication distance of 1.25 m[5].

In this paper, we introduce the narrow-band filtering technology to reduce the impact of optical noise and reduce the difficulty of image processing from the physical level, we also introduce MIMO technology into the OCC system to increase system transmission rate, and propose an LED array decoding algorithm based on the directional projection method to reduce the system delay.

The OCC system is mainly divided into three parts: the transmitter, channel and the receiver. The transmitter encodes and modulates the original data sequence to be sent to the drive circuit. The drive circuit amplifies signal to drive the LED light source to send the optical signal to the optical channel. In practical applications, OCC generally uses on-off keying (OOK) modulation, when the LED is on, the signal is "1", and when the LED is off, the signal is "0". The IS can convert the received light signal into an electrical signal, and obtain an image by converting the electrical signals corresponding to different pixel units into pixel values respectively. The image is processed to detect the light spots in the image to obtain the corresponding signal[6]. The light spot signal is demodulated, and the demodulated signal is integrated into an information stream, then the information stream is decoded to obtain the original data sequence.

In OCC field, pixels in the camera are similar to the antennas in radio frequency (RF) field. MIMO uses pixels at

* This work has been supported by the Department of Science and Technology of Jilin Province (No.20200401122GX).
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both ends of the communication system to transmit data in parallel across multiple communication links, which expands the communication capacity of the system and achieves a higher utilization rate of space resources[7]. The camera is used as a receiving antenna, and the IS in the camera is a miniature PD array, therefore a single camera can be regarded as multiple receiving antennas[8]. When there is more than one LED light source at the transmitter of the OCC system, the system can be regarded as having multiple transmitting and receiving antennas at the same time, and can combine with MIMO technology to complete the parallel reception of multiple signals. Fig.1 is the structure of MIMO-based OCC system.

The transmitter is mainly composed of the following four parts, including the data generation and data packaging module, the OOK modulation module, driving circuit, and 4×4 LED array with 808 nm wavelength.

The data update module uses the random statement to randomly generate a one-dimensional logic matrix as the binary data sequence to be sent, the data encapsulation module adds the synchronization frame used to transmit the preamble to complete the encapsulation.

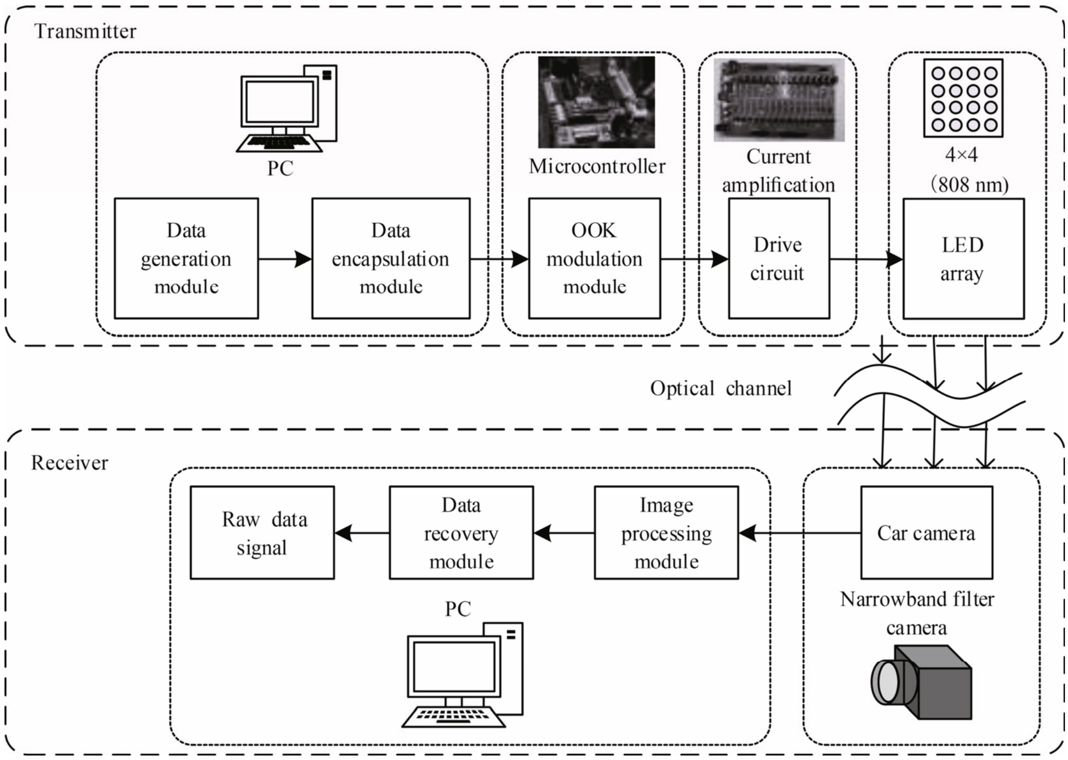

Fig.1 The structure of MIMO-based OCC system

In order to achieve robust time synchronization between each group of data sequences, the synchronization frame uses a known Barker sequence preamble with a length of 7, and the Barker sequence is {1, 1, 1, 0, 0, 1, 0}. Fig.2 is the data package structure diagram. A data packet includes a synchronization frame with a length L_H and a data frame with a length of L_D, and the information of a complete data packet needs to be continuously collected (L_H+L_D) frame images. When the data packet synchronization frame is transmitted, the positioning LEDs (four-corner LEDs) in the LED array always remain on. The "1" and "0" in the Baker sequence respectively correspond to the on and off of all the signaling LEDs in the array at a certain time. The data frame of the data packet is used to transmit valid data information, and each transmission LED is independently modulated. Each data packet has only 12 transmission LEDs to transmit data, and one data packet can transmit 12×L_D bits data.

The C8051F340 microcomputer (MCU) development board is selected, with the P2.0—P2.7, P3.0—P3.7 ports, a total of 16 I/O ports as the output port of the modulation signal. The I/O port controls the driving circuit to drive the LED array and send light signals by outputting high and low levels. When the signals "1" and "0" are sent, the I/O port outputs correspond to high and low levels, respectively.

Since the output current of the I/O port of the MCU is relatively small, the OCC system needs to amplify the current output by the I/O port of the MCU through a drive circuit to drive the LED with a suitable current.

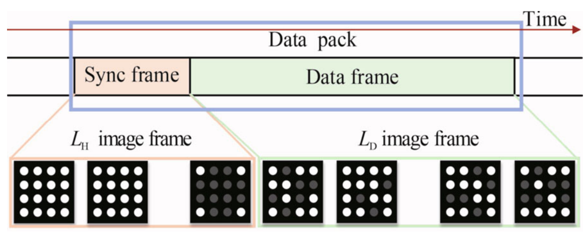

Fig.2 Data package structure diagram

In order to ensure that the current loaded on the LED is stable at an appropriate value, the driving circuit is designed with a typical triode driving LED principle. Fig.3 is the schematic diagram of LED drive circuit.

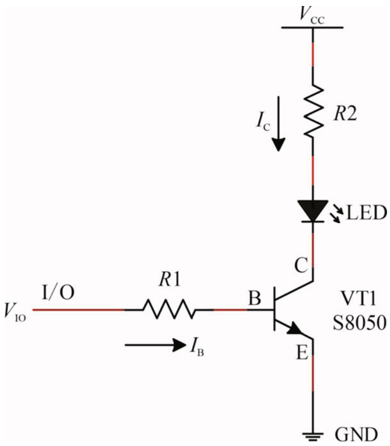

Fig.3 Schematic diagram of LED drive circuit

When the triode is working at the critical value of the amplification zone and the saturation zone, the calculation method of resistance $R1$ and resistance $R2$ is as follows

$$R1 = \frac{\beta\left(V_{IO} - V_{BE}\right)}{I_C}, \tag{1}$$

$$R2 = \frac{V_{CC} - V_{LED} - V_{CE}}{I_C}. \tag{2}$$

The voltage of the I/O port is V_{IO}=3.3 V, the conduction voltage between the base electrode of the triode and the emitter is V_{BE}=0.7 V, the magnification of the triode is β=150, and I_C is the collector voltage of the triode. V_{CC}=5 V, and V_{LED} is the voltage loaded on the LED. V_{LED} =2.4 V, and the conduction voltage between the base electrode of the transistor and the emitter is V_{CE}=0.3 V. The test results are shown in Tab.1.

The 75 mA current is selected to drive the LED, and the resistance values of $R1$ and $R2$ are respectively selected as 2.5 kΩ and 30 Ω. Fig.4 is the physical picture of LED array drive circuit.

Tab.1 Test results under different drive currents

$R1$ (kΩ)	$R2$ (Ω)	I_C (mA)	I_B (mA)	Test results
2.5	50	45	1.2	The light spot is not obvious
2.5	30	75	0.9	The light spot is bright
2.5	25	100	0.9	The light spot is too bright and the stars appear

The specific parameters of the narrowband filter camera are shown in Tab.2. The actual system is shown in Fig.5.

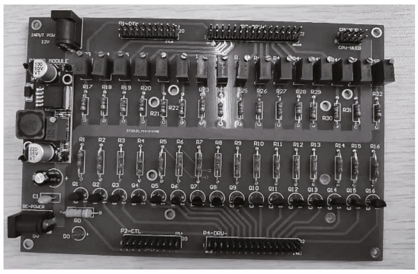

Fig.4 Physical picture of LED array drive circuit

Tab.2 Parameters of camera

Name of parameter	Value
Sensor size	1/3 CCD
Effective pixels (resolution)	720 (H)×576 (V)
Pixel size	4.75 μm×4.75 μm
Operating voltage	12 V
Focal length	6 mm
Frame rate	25 fps
Filter center wavelength	808 nm±2 nm
Filter cut-off range	200—1 100 nm

Narrowband filtering is realized by configuring 808 nm filter in front of the vehicle-mounted camera lens.

The camera is connected to the receiving end personal computer (PC) through the universal serial bus (USB) interface. The receiving PC completes the real-time acquisition and processing of the image through the OpenCV library in python to realize the image processing and the data recovery. Firstly, use videocapture statement to call the receiving camera to obtain the video image in real time, and use the read statement to read each frame of the image captured by the camera. Then, the acquired image is processed in real time through the LED array decoding algorithm to restore the original data sequence.

Fig.5 The actual system

In the MIMO-based OCC system, the pixels are a k-order (k×k) LED array, and the LEDs in the array are divided into positioning LEDs and signaling LEDs. Fig.6 is the schematic diagram of k-stage LED array. The positioning LEDs are deployed at the top left, bottom left, top right, and bottom right corners of the k-level LED array, to facilitate the determination of the position of the LED array on the image, keep it in a constant light state, and not be used for sending data information. The transmission LED is the remaining (k^2−4) LEDs in the k-stage LED array. Lights go on when the sending signal is "1", and go off when the sending signal is "0". Spatially encode a string of data to be transmitted. The transmitted data starts from the LED in the first row and second column in the k-level LED array, in the order from left to right and top to bottom arrange in sequence until the end of the LED in the k-th row and (k−1)-th column.

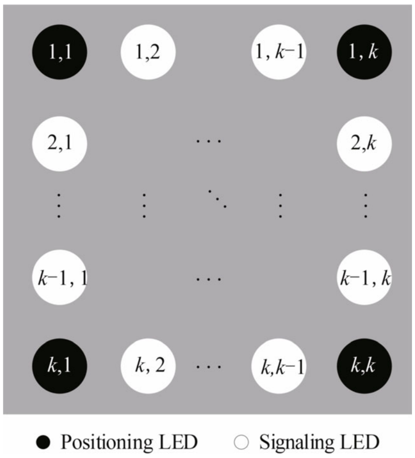

Fig.6 Schematic diagram of *k*-stage LED array

The decoding steps are described as follows.

Step 1. Convert the image received by the receiving end from an RGB image to a grayscale image, and binarize the grayscale image through a certain threshold to obtain a binary image I.

Step 2. Use the image processing method to detect all the LED light spots in I, and get the corresponding information of the light spots. According to all the spot information that has been obtained, the maximum value of the horizontal and vertical coordinates of the center of the spot in the LED spot array can be found.

Step 3. Since the positioning LEDs are always on and deployed at the four corners of the array, the horizontal and vertical coordinates of the center of the positioning LED spot must be the maximum values of the horizontal and vertical coordinates of the center of the LED spot in the entire LED array. Therefore, the center coordinates of the positioning LED spot in the lower left corner, upper left corner, lower right corner, and upper right corner of the array can be expressed as $(\hat{x}_{\min}, \hat{y}_{\min})$, $(\hat{x}_{\min}, \hat{y}_{\max})$, $(\hat{x}_{\max}, \hat{y}_{\min})$, $(\hat{x}_{\max}, \hat{y}_{\max})$. According to the center coordinates of the four locating LED spots, the ideal center coordinates of the LEDs in the m-th row and n-th column of the LED array in the image $(x_{\mathrm{LED},m}, y_{\mathrm{LED},n})$ can be calculated as follows

$$\begin{cases} x_{\mathrm{LED},m} = \left[\hat{x}_{\min} + \left(\dfrac{\hat{x}_{\max} - \hat{x}_{\min}}{k-1}\right) \times (m-1) \right], & 1 \le m \le k \\ y_{\mathrm{LED},n} = \left[\hat{y}_{\min} + \left(\dfrac{\hat{y}_{\max} - \hat{y}_{\min}}{k-1}\right) \times (n-1) \right], & 1 \le n \le k \end{cases}, \tag{3}$$

$$\boldsymbol{S}_{mn} = \begin{cases} 1, & I(x_{\mathrm{LED},m}, y_{\mathrm{LED},n}) = 1 \\ 0, & I(x_{\mathrm{LED},m}, y_{\mathrm{LED},n}) = 0 \end{cases}. \tag{4}$$

Step 4. Judging whether there is a spot at the center coordinates of each LED by Eq.(4), the LED state matrix $\boldsymbol{S}$ is obtained. If $\boldsymbol{S}_{mn}$=1, there is a light spot, and the LED at row m and column n of the LED array is on, and the carrying signal is decoded as "1". If $\boldsymbol{S}_{mn}$=0, there is no light spot, and the LED at row m and column n of the LED array is off, and the carrying signal is decoded as "0". After converting $\boldsymbol{S}$ into a series of data sequences, the data represented by the positioning LEDs in the sequence need to be removed to restore to the original data sequence containing (k^2−4) bits.

We use an LED array decoding algorithm based on the directional projection method. This method is to accumulate the value of the target pixel value in each row or column of the image. Through the value of the target pixel, the position and boundary of the detected target can be judged, which helps to distinguish the target area from the background. According to the direction of the accumulated pixels, it is divided into a vertical projection method for each column of the accumulated image and a horizontal projection method for each row of the accumulated image. Through the vertical and horizontal directions of the image Projection can distinguish the LED spot from the background, and obtain the position and boundary of each LED spot.

Decoding process of LED array decoding algorithm based on directional projection method is shown in Fig.7. The steps to determine the region of interest (ROI) area and decode based on the directional projection method are as follows.

Step 1. After the original image (a) is grayed and binarized, the binary image (b) is obtained.

Step 2. Using the directional projection method, the obtained binary image is projected in both horizontal and vertical directions, and the horizontal and vertical pixel projection histograms of the binary image are obtained. The vertical and horizontal pixel projection histograms are shown in (c) and (d), respectively.

Step 3. By analyzing (c) and (d), the number of pixel rows (columns) $\hat{x}_{\min}, \hat{x}_{\max}, \hat{y}_{\min}, \hat{y}_{\max}$ corresponding to the leftmost peak and the rightmost peak of the pixel projection histogram in the vertical and horizontal directions is obtained. According to the number of pixel rows and columns, the position of each row and column of the LED array can be estimated by Eq.(3).

Step 4. According to Eq.(4), the state of the corresponding

LED is judged according to the pixel value at each LED position, and the LED state matrix $\boldsymbol{S}$ is obtained by Eq.(5).

$$\boldsymbol{S}=\begin{bmatrix}1 & 1 & 0 & 1\\ 0 & 1 & 0 & 0\\ 0 & 1 & 1 & 1\\ 1 & 0 & 0 & 1\end{bmatrix}. \tag{5}$$

Step 5. According to $\boldsymbol{S}$, the 12-bit original data sequence carried by the LED array is decoded, and the decoding is completed. The original data sequence is shown in (e).

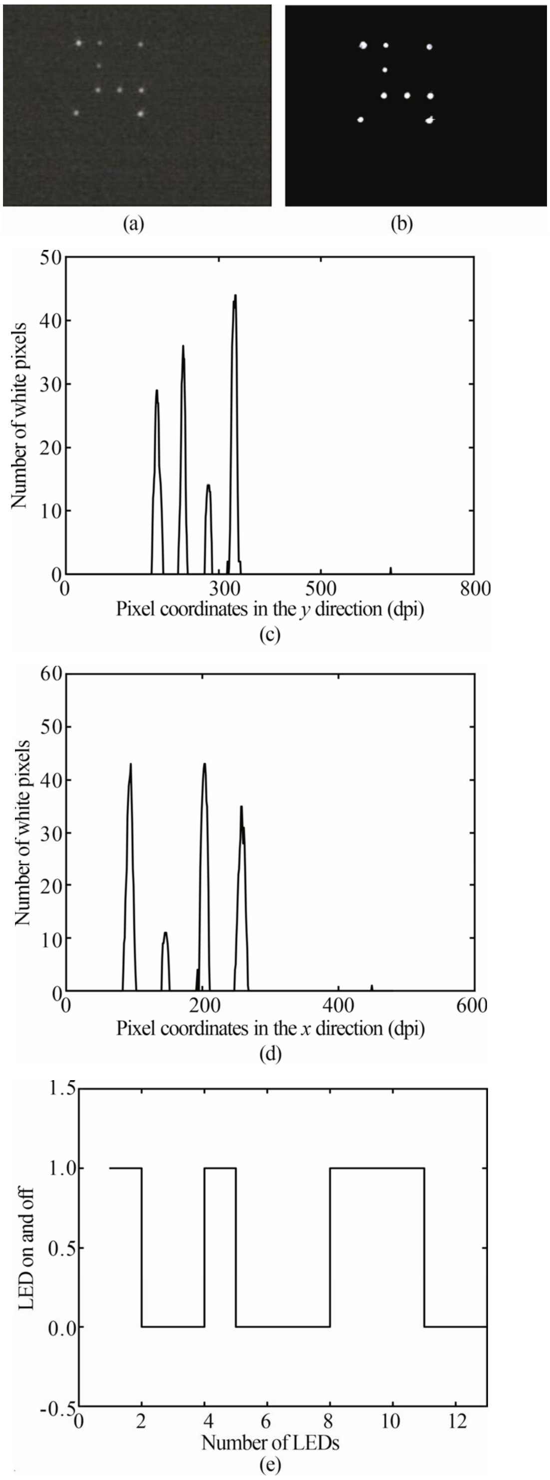

Fig.7 Decoding process：(a) The original image; (b) Binary image; (c) Vertical projection; (d) Horizontal projection; (e) Decoding result

The CPU is the INTER Core I3-4330 and the windows 8 system platform, the software MATLAB R2015a is used as the decoding platform. Then, we will conduct a performance analysis on the processing delay and bit error rate (*BER*) of the decoding algorithm of the system, and compare it with the LED decoding algorithm based on Hough circle transform and connected domain labeling proposed in Refs.[9] and [10].

It can be seen from Fig.8 that the average processing delay of the LED array decoding algorithm based on the directional projection method is maintained at about 0.02 s, and does not change with the change of order, while the average processing delay of the other two decoding algorithms is affected by order.

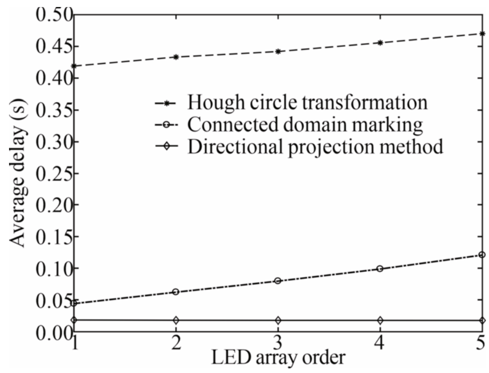

Fig.8 The average delay curves

We analyze the variation of the *BER* of the three decoding algorithms with the spot radius. *BER* at various spot radii is shown in Fig.9. When the LED spot is blurred, under the same blurred condition, the LED array decoding algorithm based on the directional projection method has a lower *BER* than the other two algorithms.

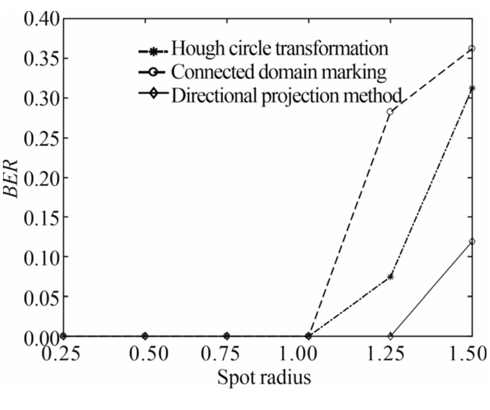

Fig.9 *BER* curves at various spot radii

Under the same communication conditions, the LED array decoding algorithm based on the directional projection method has the smallest processing delay and bit error rate compared with the other two algorithms. In order to ensure the communication performance of the system, the LED array decoding algorithm based on the directional projection method is more suitable for the OCC system in this paper.

In the OCC system, the communication distance is a key factor affecting the communication performance of the system. This section mainly analyzes the *BER* of the MIMO-based OCC system implemented under different communication distances, and obtains the maximum communication distance that the system can reach under the premise of normal communication. The experiment starts from the position where the LED array at the transmitter is 0.5 m away from the camera lens at the receiver, and tests are performed every 0.5 m. The test results are shown in Fig.10.

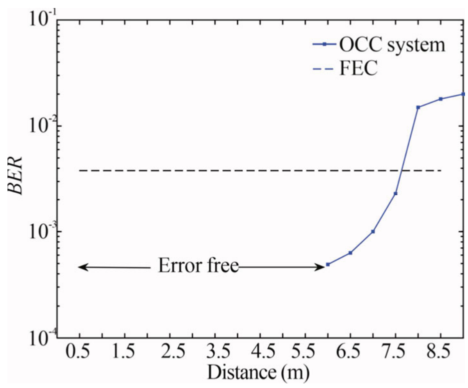

Fig.10 *BER* at various communication distances

We can see that within the communication distance from 0.5 m to 5.5 m, the OCC system implemented has no error generated, when the communication distance is within 7.5 m, the error generated by the system can be corrected by forward error correction (FEC).

In summary, this article introduces MIMO technology into the OCC system to increase the system transmission rate. The LED array decoding algorithm based on the directional projection method is used to achieve low latency and low *BER* performance. When the LED array at the transmitter of this system flashes at a frequency of 12 Hz and the frame rate of the on-board camera at the receiver is 25 fps, the transmission rate can reach 126.32 bit/s. When the LED array order increases to 10, the transmission rate reaches kilo bits per second level, which can meet the requirements of the IEEE802.15.7 standard for the VLC transmission rate. In this paper, the research lays the foundation for the subsequent optimization and improvement of the system.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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