Breaking the Throughput Limit of LED-Camera Communication via Superposed Polarization

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***Abstract*—With the popularity of LED infrastructure and the camera on smartphone, LED-Camera visible light communication (VLC) has become a realistic and promising technology. However, the existing LED-Camera VLC has limited throughput due to the sampling manner of camera. In this paper, by introducing a polarization dimension, we propose a hybrid modulation scheme with LED and polarization signals to boost throughput. Nevertheless, directly mixing LED and polarized signals may suffer from channel conflict. We exploit well-designed packet structure and Symmetric Return-to-Zero Inverted (SRZI) coding to overcome the conflict. In addition, in the demodulation of hybrid signal, we alleviate the noise caused by polarization on the LED signals by polarization background subtraction. We further propose a pixel-free approach to correct the perspective distortion caused by the shift of view angle by adding polarizers around the liquid crystal array. We build a prototype of this hybrid modulation scheme using off-the-shelf optical components. Extensive experimental results demonstrate that the hybrid modulation scheme can achieve reliable communication, achieving 13.4 kbps throughput, which is 400 % of the existing state-of-the-art LED-Camera VLC.**

***Index Terms*—Visible Light Communication, Polarization, Hybrid Modulation**

I. Introduction

Visible light communication (VLC) has received extensive attention and become an alternative to radio frequency communication due to its wide spectrum of advantages, including the large frequency band and channel capacity, as well as high security [1]–[6]. However, it is still difficult to implement existing VLC approaches in reality because of their high requirements on the hardware components, such as the Light Emitting Diodes (LEDs) with high frequency response or the Photo-Diodes (PDs) with high sampling rate [7]–[10]. Recently, researchers have set their sights on practical VLC systems that only involve commercial-off-the-shelf (COTS) devices. Benefiting from the widespread deployment of LED luminaires and the proliferation of camera-equipped smartphones, LED-Camera VLC becomes a promising solution. A LED-Camera VLC system usually uses COTS LEDs as the transmitter and camera (widely adopted in portal devices, e.g., smartphones) with rolling-shutter effect as the receiver [11]–[17]. However, there seems an impenetrable barrier for current LED-Camera VLC towards high throughput. Due to the sampling manner of rolling shutter, the throughput of LED-Camera VLC is limited to less than 5 kbps, which hinders the real implementation of existing LED-Camera VLC systems.

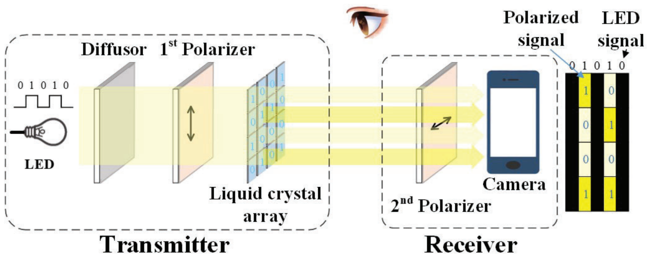

Fig. 1: Illustration of our hybrid modulation design. LED and LC array modulate data together. Human eyes are insensitive to polarized light, while the receiver can obtain LED signals and polarized signals simultaneously by attaching a polarizer in front of camera.

The throughput of LED-Camera VLC is essentially constrained by the dimensionality of the data received by the rolling shutter-based camera. In general, the pixels of a single frame of the camera with rolling shutter effect are sequentially sampled column by column. The number of columns is restricted by the effective resolution of the image sensor in the camera. Bit '1'/'0' is modulated by turning ON/OFF the LED in traditional OOK modulation [11], and the bright/dark luminance forms bright/dark bands ('1'/'0') in a frame. Therefore, multiple data-carrying bands can be received in a frame. Since a column of pixels (i.e., a band) can only represent one bit of information, a frame can only carry 'one-dimensional data'. For example, as shown in Fig. 1, if LED modulates data '01010' by turning ON/OFF LED, the receiver can observe bright/dark bands of LED signals.

In this paper, we aim to remarkably increase the throughput of LED-Camera VLC by superposing extra dimensions. The key idea is to utilize polarization for this augmentation. Specifically, we circumvent the data limit in a band of conventional rolling shutter by adding a polarized light array. As illustrated in Fig. 1, we add a polarizer and a liquid crystal (LC) array in front of the light source (i.e., LEDs) to produce polarized light. A diffusor[1] is used to soften the light intensity and

[1]Diffusor is often used in lighting infrastructure to avoid damage to human eyes caused by high-intensity light emitted by LEDs.

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produce uniformly polarized light. In this way, the camera can receive multiple bits modulated by polarized light in a band by adding another polarizer film in front of the camera. This hybrid modulation scheme not only preserves conventional LED-Camera channel, but also introduces a new polarized channel. Since such a design is inexpensive and convenient to deploy on current LED luminaires [18], [19], we believe that this hybrid scheme will break the limitation of LED-Camera VLC in real implementations.

However, the above solution raises a conflict between the LED signal and polarized signal. That is, during the modulation process, LED will turn off if modulating a bit '0'. In this dark state, polarization modulation cannot be performed. In a nutshell, the LED signal and polarized signal cannot coexist in the dark state. To solve this issue, we propose a novel encoder - Symmetric Return-to-Zero Inverted (SRZI) and a well-designed packet structure according to the response time difference between the LED and LC. The insight behind SRZI is that bright bands appear alternately in two consecutive frames. With this coding strategy, the polarized signal can be recovered by splicing bright bands in these two frames. Eventually, the LED signal and polarized signal can be concurrently transmitted.

In practice, we also encounter two challenges in the demodulation. First, since the LED signal is mixed with some noise caused by polarization, the signal-to-noise (SNR) ratio of the LED-Camera channel would be reduced, degrading the demodulation accuracy. Second, unlike the pure-polarized VLC [18], [19], the LC array in our scheme suffers from perspective distortion [20], [21] caused by the variation of view angle. To solve this problem, traditional solutions [22]–[24] set extra markers as the positioning assistance, like the three position markers in a QR code [22], which usually occupy certain number of pixels in the corners. However, it is hard to be applied to our scheme because the limited number of pixels in the LC array can hardly afford extra markers.

To tackle the first challenge, we exploit the similarity of polarized signal among multiple frames during the polarization modulation to alleviate the noise in the bright bands. This significantly improves the SNR of LED signals. For the second challenge, we place a piece of polarizer around the LC array on the transmitter's side. The polarizer outlines the boundary of the LC array. In particular, the polarization direction of this polarizer is deliberately set to be different from that of the polarized light. Additionally, a dispersor is used to divert polarized light into different colors. On the receiver's side, we can detect the boundary (including corners) of the LC array according to color difference. This treatment is inspired by our observation on the insensitivity of human eye to the directionality of polarized light [18], [19], [25]. In this way, our scheme achieves the effect of 'corner positioning' in a pixel-free fashion.

We prototype our scheme with COTS devices: a lamp to modulate visible light, a modified 128x64 LC array to create polarized lights, and a smartphone to receive the hybrid signal of light and polarization. We perform extensive experiments and the results show that our scheme can achieve reliable communication with a throughput of 13.4 kbps, which is 400 % of the existing state-of-the-art LED-Camera VLC. In summary, the contributions of this paper are as follows.

- We propose a new hybrid modulation scheme supported by the transmission of LED signal and polarized signal concurrently. The proposed scheme utilizes a novel symmetric coding mechanism and packet structure to achieve hybrid signal transmission, breaking the limitation of data dimension in conventional LED-Camera VLC.
- Leveraging the biological fact that humans' eyes are insensitive to the direction of polarized lights, we propose to employ a polarizer to enable corner positioning of perspective distortion image in a pixel-free way.
- We build a prototype of our scheme and conduct extensive experiments. The results demonstrate that our scheme can tremendously boost the throughput of LED-Camera VLC, and its cost-efficient and COTS implementation will facilitate the VLC deployment in practice.

The rest of this paper is organized as follows. We introduce the background of LED-Camera communication and polarized light modulation in Sec. II. The hybrid modulation scheme is presented in Sec. III. In Sec. IV, we propose the demodulation method in hybrid signals. We report and discuss the evaluation result in Sec. V. We conclude our paper in Sec. VII.

II. Background and Related Work

In this section, we briefly introduce the rolling shutter effect and polarization modulation. Meanwhile, we investigate existing LED-Camera and polarization communication approaches in the literature.

A. LED-Camera Communication

Rolling shutter effect is the basis of LED-Camera communication. The rolling shutter-based camera exposes and samples the pixels of a single frame in a column-by-column manner. If using On-Off Keying (OOK) to modulate bit '1'/'0', i.e., turning the LED ON/OFF, a certain number of bright/dark bands in a frame can be captured by the camera, as shown in Fig. 2. By demodulating the captured bands, the receiver can retrieve the transmitted information. In addition, the flicker frequency of VLC should be greater than 200 HZ [1], with the consideration of lighting function of VLC and avoiding visible flicker of data transmission from harming human eyes.

There are two types of LED-Camera communication systems according to whether the influence of the gap [26], [27] between frames is involved or not. As illustrated in Fig. 3 , the data modulated by LED is lost in the frame gap. Traditional LED-Camera communication systems do not take this gap into account and achieve a throughput of 3.1 kbps at a distance of 12 cm by using OOK modulation [11]. The throughput is still lower than 3.2 kbps, even enhancing the LED-Camera communication via high-order modulation (e.g., GSK [16] or CASK [15], which increase the data size carried in each band). To achieve higher throughput, recent researchers adopt colorful LED luminaires for data transmission and improve

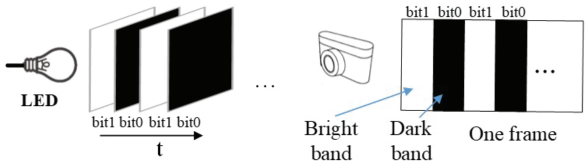


Fig. 2: Rolling shutter effect. The LED transmits data through rapid changes of the ON/OFF state, which are captured by the rolling shutter-based camera as bright/dark bands.

the throughput to 7.7 kbps [28]. Nevertheless, these colored LEDs cannot be used in commercial lighting infrastructure that usually applies white LEDs.

By involving the aforementioned frame gap, researchers [14], [27] propose to use Frequency-Shift Keying (FSK) to achieve a more robust demodulation scheme, but its throughput is only 11.32 Bps. In addition, IoTorch [26] uses packet repetition in one frame and decodes packets via header detection, enabling a 2.92 kbps throughput. Its packet structure is shown in Fig.3. The frame can capture a complete packet within a repetition mechanism.

Albeit the improvement in the data rate (i.e. throughput), the throughput of existing studies is still limited by the number of bands in the frame. Considering the high-throughput requirement for the VLC system in IEEE standard [1], i.e. the required minimum data rate is 11.67 kbps, there is an urgent need to break the data rate limitation of LED-Camera communication.

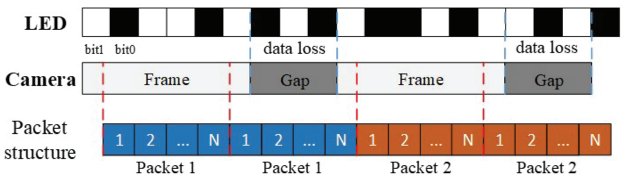


Fig. 3: A repetition packet structure with a gap between two continuous frames.

B. Polarized Light Modulation

Recently, the polarized light is utilized for LED-Camera VLC [18], [19], [29]. POLI [19] achieves flicker-free polarized light communication by using multiple LEDs. In this method, each LED deploys a polarizer with a different polarization direction, realizing 71 Bps throughput. The systems in [18], [29] employ a single LC cell to modulate data by changing polarized light to different directions. As shown in Fig. 4, the incident light is converted to polarized light by a polarizer. Then, the polarization direction of this polarized light is diverted by the LC cell. If no voltage is applied to the LC, the direction of the incident polarized light will be rotated 90°. The dispersor diverts this light into different color beams with various polarization directions. The second polarizer enables a polarized color beam to pass where the polarization direction of the beam is the same as this polarizer. If a voltage is applied, the polarization direction of the light is rotated with the change

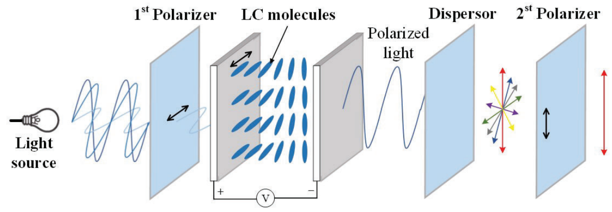


Fig. 4: Illustration of the principle of liquid crystal rotating polarized light. Visible light is converted to polarized light by the first polarizer, which is then rotated by the liquid crystal. The dispersor transfers polarized light into color beams. The second polarizer outlies colors different from the polarization direction and retains one color of the light beam.

of the voltage, thereby changing the polarized color beam. Different colors can be used to represent various information. However, these works can only achieve a throughput of fewer than 1 kbps owing to the limitation of LC response time [30].

In this paper, we break the throughput limit of LED-Camera communication by exploring a new polarization dimension. By adding an LC array, the bright band in a frame can additionally carry polarized signals to increase the overall data rate.

III. Hybrid Modulation Design

We aim at boosting the throughput of LED-Camera communication by introducing a polarization dimension to enable hybrid modulation. For doing so, intuitively, we can simultaneously mix and transmit the LED signal and polarization signal, and then receive them at the camera end. However, there is a conflict between the LED channel and polarization channel when these two kinds of signals are transmitted concurrently. Specifically, since the LC array itself cannot emit light, it requires an extra light source to empower its signal transmission. In our hybrid modulation scenario, the LED plays the role of such a light source. However, LED will be turned off when generating a dark band. At this time, due to the 'downtime' of the light source, the polarization signal will be lost.

In this section, we first study the hybrid modulation that can maximize the throughput of the hybrid signals, in which we meet the challenge of channel conflict (Sec. III-A). Then, in Sec. III-B, we design a special packet structure based on the response time difference between the LED and LC. With this packet structure, we can well modulate hybrid signal and localize frames with conflict. After that, we overcome the channel conflict by splicing LED packets in adjacent frames with SRZI coding as described in Sec. III-C. Our eventual hybrid modulation scheme is detailed in Sec. III-D.

A. Challenge of Hybrid Modulation

Generally, the frequency response of commercial LED can reach a few MHz [31], and its response time is much less than the sampling period of the rolling shutter camera. Even for the advanced smartphone camera (e.g. Samsung ISOCELL HMX with 12032 $\times$ 9024 pixels [32]), the sampling frequency (10 kHz) is less than the frequency response of LED. Therefore,

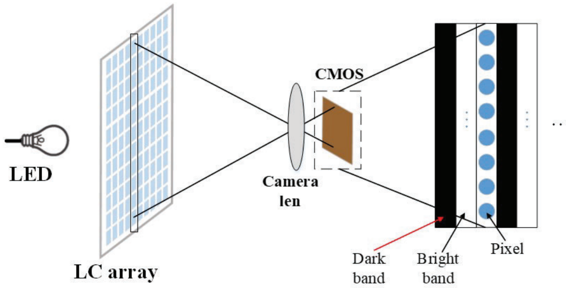


Fig. 5: Illustration of hybrid modulation. The LED and LC array transmit data simultaneously, and CMOS camera receives the hybrid signal. The LED signal is represented by bands, and the bright bands of column pixels contain polarized signals.

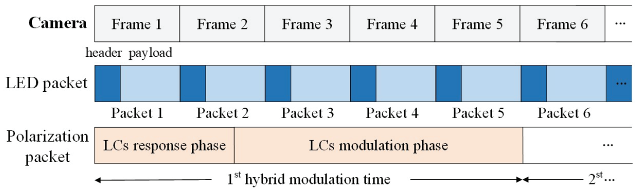


Fig. 6: Structures of the LED packet and the polarization packet in the hybrid modulation. A LED packet can be carried in a frame, while a polarization packet spans five frames.

the relatively low sampling frequency of the rolling shutter camera is the bottleneck limiting the throughput of LED-Camera VLC.

In traditional LED-Camera communication, the intensity of pixels in one column is the sum of the optical energy in the exposure duration. These pixels can only represent one bit of information quantified by the intensity. We aim to increase the data rate of LED-Camera communication by introducing a polarization channel, i.e., hybrid modulation with LED and polarization signals. To maximize the throughput gain brought by the introduction of the polarized channel, we want each column to carry as much data as possible. This can be realized by adding a LC array in front of the LED, as shown in Fig. 5. Such a design enables the camera to receive multiple polarized signals in each column, making full use of each column's pixels. This hybrid modulation increases the dimensionality of the data carried by a band on the basis of the original LED-Camera communication. Here, we use bit mapping to modulate the polarized signal.

However, the above modulation scheme also induces a conflict between the LED signal and the polarization signal. When the LED modulates bit '0', the LED is turned off, resulting in the absence of the light source for the LC array. The camera cannot receive any polarized signal in the dark band, leading to the loss of information in the polarization channel. To address this challenge, in the following two subsections, we propose a well-designed packet structure and a Symmetric Return-to-Zero Inverted (SRZI) coding strategy. With these two countermeasures, we can recover the lost polarized signals to maximize the benefit brought by the hybrid modulation.

B. Packet Structure Design

Despite the essential conflict between the LED signal and the polarization signal, we find that there is a large difference between these two signals in the time domain. Due to the diversity of hardware, the time spent in modulating the LED signal and the polarized signal is different. To be specific, the frequency response of LED is much higher than the sampling frequency of the camera. In traditional LED-Camera VLC, one frame can take in 100-200 bands of LED signals. The duration of a band is about 0.15 ms [26], while the modulation element of polarized light, i.e. LC, has a response time larger than 10 ms [33], [34]. Therefore, the response time of LC is much longer than that of LED. Based on this response time difference, we design a packet structure for the hybrid modulation. The illustration of the packet structure without considering the gap between frames is shown in Fig. 6. One LED packet is contained in a frame, while modulating one polarization packet needs five frames. Each LED packet has a header to indicate the beginning of the data transmission, and a payload to carry the data. The polarized signals are modulated based on the polarization state of LC cells. The modulation of the traditional LC can be divided into two stages: the response phase and modulation phase [30]. Since the LC cell cannot accurately express data within the response phase (the direction of the LC molecules changes slowly, and the direction of the polarized light cannot be immediately twisted by the LC during the response phase), the polarization packet can only be transmitted stably after the LC cell completes the rotation of polarization direction. In the first and second frames, only LED packets can be detected because the LC cell is in the response phase. The camera is able to detect stable polarization packet and LED packet simultaneously from the third frame to the fifth frame. After that, we only need to solve the packet collision issues in the third to fifth frames. In this paper, we define that one *hybrid modulation time* is the period of sampling five frames, including two frames with LED signals and three frames with hybrid signals.

C. Symmetric Return-to-Zero Inverted Coding

We note that the polarization packet is unchanged from the third frame to the fifth frame. In addition, the hybrid modulation time contains lots of bright bands of the LED signal. To address the problem of packet collision, we propose to splice adjacent frames with bright bands to recover the polarization packet. We first align two LED packets of adjacent frames by using a strict time control of modulation. For example, when the camera has 30 frames per second (fps), the total duration of the packet in one frame can be set to 1/30 seconds[2]. As Case 1 in Fig. 7 illustrates, we can recover the polarization packet by splicing the bright bands in two packets to form an image. For example, the first bit (i.e., the first location) of the third packet is '1', where the LED was turned

[2]The high frequency response of the LED allows us to control the LED signal with high precision to reach microsecond level, so the offset of LED packets is very small.

on to generate a bright band. The bit in the same location (i.e., the first bit also) of the fourth packet is ‘0’, where the LED was turned off to generate a dark band. Since the camera cannot receive the polarized signal in a dark band, we discard the dark band of the fourth packet and take the bright band of the third packet as the first band of the spliced image. For each of the following locations in the two packets, if that of any packet is a bright band, we can choose the bright band to get an image filled with bright bands. In this way, the conflict between the LED signal and the polarized signal in Case 1 is avoided.

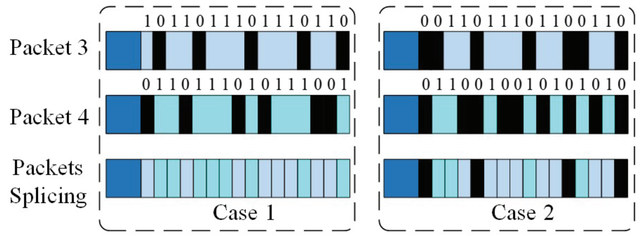


Fig. 7: Bright bands extraction from two packets in adjacent frames of one hybrid modulation time. Case 1: the polarization packet can be successfully recovered with spliced bright bands. Case 2: the polarization packet cannot be recovered when two packets have bit ‘0’ at the same location.

However, if there is a location where both two packets have bit ‘0’, no bright bands can be used to recover polarized signals in this location, as Case 2 shown in Fig. 7. To solve this problem, we propose an encoder - Symmetric Return-to-Zero Inverted (SRZI) coding. As shown in Fig. 8, we first apply 4B6B Run Length Limit (RLL) coding for DC balance and flicker mitigation [1]. The 4B6B coding can eliminate the bit sequences that contain more than three consecutive ‘1’/‘0’ by generating 6 encoded bits for every 4 bits (the detail of 4B6B mapping is in Table 4 of [1]). Then, we can perform SRZI coding on the two adjacent packets in Case 2 to eliminate the dark bands. For the third frame, SRZI coding requires bit ‘1’ to be modulated using high amplitude, and bit ‘0’ to be represented using one low amplitude and one high amplitude. As for the fourth frame, bit ‘0’ is modulated with one high amplitude and one low amplitude which is symmetric to the third frame. With this treatment, there is always a high amplitude at any location of two packets with bit ‘0’ as shown by the blue area in Fig. 8. By using SRZI coding, the bright band can always be found in two packets that need to be spliced. Since the coding efficiency of 4B6B is $2/3$ [1], we only use 4B6B and SRZI coding for the third frame to the fifth frame. Other frames in the hybrid modulation time can be encoded by more efficient encoders (e.g. GSK [16] or ASK [15]).

Although this coding scheme can effectively avoid channel collision, we encounter problems of the packet shift caused by the asynchronization of LED-Camera communication and the gap between two successive frames. The gap will cause the polarized signal not to be fully recovered from one LED packet

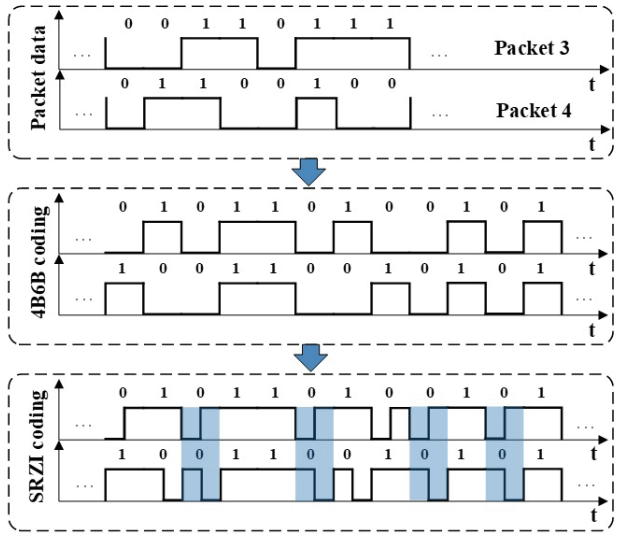


Fig. 8: Two packets are encoded with 4B6B and SRZI. These two packets first apply 4B6B for flicker mitigation, and then are encoded with SRZI for dark band elimination.

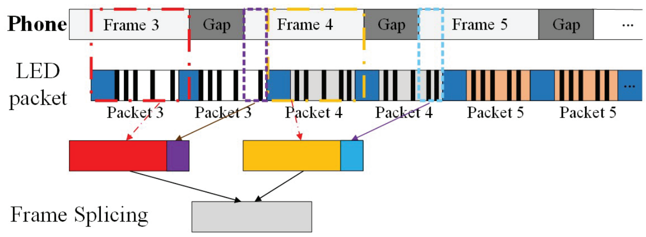


Fig. 9: Combining two parts of packets appeared in three frames to overcome the shift of packet in one hybrid modulation time.

since the repetition packet structure (as shown in Fig. 3). The packet shift issue will lead to a part of the third packet shift to the fourth frame, as shown in Fig.9. This may cause the packet splicing in the third frame to fail. Similarly, the fifth frame owns the part of the fourth packet. To address this issue, we propose a frame splicing method based on our observation that the length of the packet approximately equals the length of the frame. Particularly, we first calibrate the packet shift. The position at the beginning of the fourth packet is calculated according to the header of the fourth packet, and the part of the third packet in the fourth frame is obtained through image clipping. Since the frame length and packet length are almost equal, the complete third frame containing the third packet can be obtained by splicing the two parts of the third packet. Similarly, the complete fourth frame containing the fourth packet can be obtained by splicing the two parts of the fourth packet, as shown in Fig. 9. Then, the polarized signal can be recovered by splicing the two frames. Note that we need at least three frames to recover the polarized signal due to packet shift.

With the above countermeasures, we can overcome the packet collision by recovering polarized signals from the

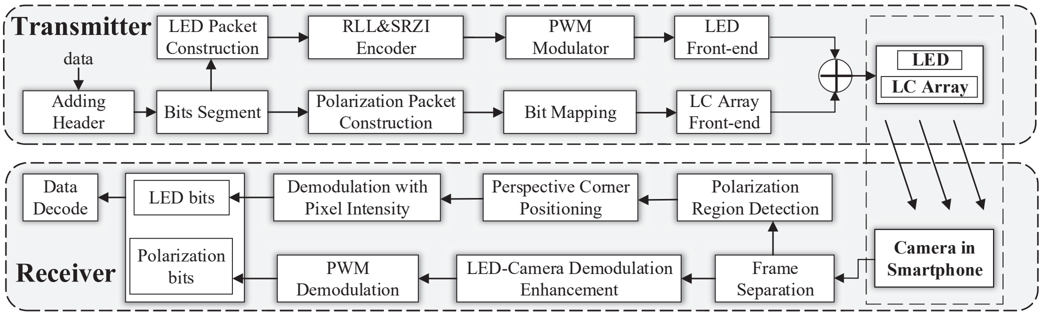


Fig. 10: Block diagram of the hybrid modulation scheme. We introduce a polarization dimension on the basis of LED for boosting the throughput.

spliced image and modulating LED signals with SRZI coding.

D. Hybrid Modulation Scheme

Fig. 10 shows the block diagram of our hybrid modulation scheme. On the transmitter's side, a header is added to the data at first. Then, the data is segmented into LED packets and polarization packets by calculating the maximum number of bits that the LED and the LC array can hold in one hybrid modulation time. The bits containing the header are assigned to the LED packets and the remaining bits are assigned to the polarization packets. Due to the gap between two continuous frames, the LED packets needs to transmit two identical packets in one frame to avoid data loss in the gap. The conflicting LED packets introduced in Sec. III-B are encoded with 4B6B and SRZI coding. Next, the LED packets are modulated using pulse-width modulation (PWM) [26] and transmitted to the LED front-end. The polarization packets are transmitted to the LC array front-end by bit mapping. Here, we use four LC cells to modulate one bit. High-order modulation [29] can be used to represent multiple bits with a single LC cell to improve the throughput. We leave it as future work. After the above process, the data will be transmitted through modulated light.

IV. Demodulating Hybrid Signals

After the camera receives hybrid signals, we first perform frame separation to obtain frames containing LED packets and the splicing image carrying polarization packets, as shown in Fig. 10. Then, a LED signal enhancement method is used to eliminate the noise of polarized signals. We will detail this method in Sec. IV-A. We demodulate LED signals by rising edge detection [26]. For the image carrying polarized signals, we first perform polarization region detection (Sec. IV-B). Then, the corners of the LC array are determined by our proposed corner positioning method (Sec. IV-C). Finally, the polarized signals are demodulated based on the pixel intensity. The data will be decoded by combining LED bits and polarization bits.

A. LED Signal Enhancement

In the hybrid modulation, the LED signals are affected by polarized signals. Typically, the bright/dark bands of LED signals are demodulated by rising edge detection or polynomial

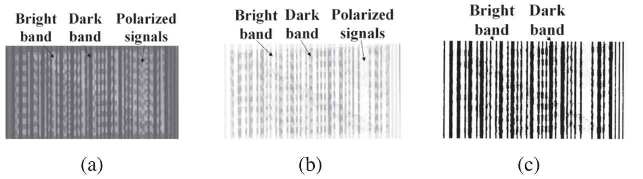


Fig. 11: Noise elimination by subtracting polarization background. (a) The noise of polarized signals in the bright band. (b) The result of noise elimination. (c) LED signal recovered by combining (a) and (b).

fitting [11], requiring bands to have high SNR[3]. However, polarized signals in bright bands decrease the SNR of the LED signal, which reduces the demodulation accuracy. Specifically, polarized light uses the polarization state to modulate data. When the LC cell applies a voltage, the second polarizer blocks the polarized light. Such a block increases the noise of the bright bands. Furthermore, the noise varies with different bright bands. As shown in Fig. 11(a), the SNR of bright bands carrying polarized signals is 0.18. These bright bands with low SNR greatly hinder the demodulation accuracy.

To deal with the above-mentioned problem, we propose to use polarization background subtraction to increase the SNR. Thanks to our designed special packet structure, in each hybrid modulation time containing five frames, the polarized signals do not vary with the frames. We take the splicing image described in Sec. III-C as the background of these five frames. The noise of polarized signals on bright bands is eliminated by subtracting the polarization background. In this way, we get bright bands with high SNR of 0.97, as shown in Fig. 11(b). Finally, we extract dark bands in Fig. 11(a) to obtain enhanced LED signals, as shown in Fig. 11(c). Then, we can demodulate LED signals with rising edge detection [26].

However, the polarization state of a LC in the response phase is different from that in the modulation phase. The polarization background in the modulation phase is not exactly the same as that in the response phase. To alleviate the polarization noise of the frames within the response phase of the LC (e.g., the first and second frames), we compare

[3]SNR is calculated by dividing the mean of the bright bands by the white pixel value of 255.

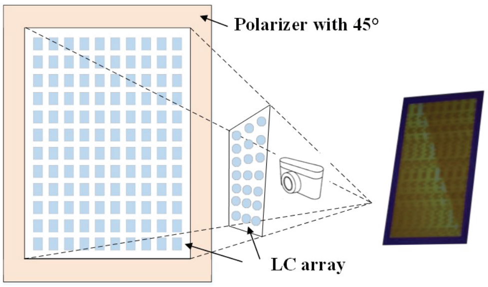


Fig. 12: Perspective distortion due to the shift of view angle. A polarizer is attached around the LC array to detect the polarized signal region.

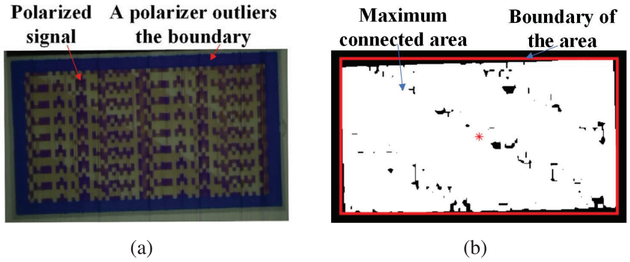


Fig. 13: The region of the LC array is outlined by a polarizer. (a) The raw image of polarized signals with a special color around LC array. (b) The rectangle boundary around the LC array is determined by using region measurement.

two polarization backgrounds, in which one is the previous splicing image and the other is the present splicing image. After respectively subtracting the first frame to these two splicing images, we take the differences with less noise as the final result.

B. Region Detection of LC Array

The polarized signal can be demodulated with the splicing image as described in Sec. III-C. However, the shift of view angle of camera may cause the problem of perspective distortion [20], [21] of LC array. As shown in Fig. 12, the shape of the LC array may be distorted when the camera receives polarized signals from an angle.

Traditional camera-based communication requires extra pixels inside the pixel array to form positioning markers. For example, the valid region in QR code can be detected by adding positioning markers at three corners [22] or the centre with color pixels [23], [24]. However, all of these region detection methods require the use of internal pixels to form positioning markers, which is hard to be applied for data modulation in LC array with limited pixel resource. To address this challenge, we propose a pixel-free positioning approach. We take advantage of hybrid modulation to extend positioning markers to the periphery of the LC array without sacrificing LC cells. Specifically, we attach a polarizer that intersects the polarization direction of polarized signal with $45°$ around the LC array, as shown in Fig. 12. Moreover, inspired by [18], we add a dispersor in front of the array to differentiate the polarization direction of this polarizer. The dispersor is able to convert the polarized light in different directions into different colors. Building on this, we are able to observe a special color around the LC array that is different from the color of polarized signals. The LC array region can be detected by identifying this special color shown in Fig. 13(a). To be specific, we first convert the splicing image to the YCbCr color space [35], highlighting the boundary of LC array. Next, the maximum connected area of the image, which is the region of the LC array, is captured by using region measurement [36], as shown in Fig. 13(b).

C. Corner Positioning

Perspective correction requires knowing the corner coordinates of the region [20], [37], [38]. To this end, we first filter out the image noise caused by edge blur. We use the dilation and erosion operation in the field of morphological image processing for filtering. Here, we apply the square structuring element for morphological operation. Then, we extract the edge points of the LC array, as shown in Fig. 14(a). The coordinates of these edge points are easy to be calculated from the binarized image by using region boundary tracing algorithm [39]. Finally, we can obtain four corner coordinates according to the largest distance from the centroid to edge points, as shown in Fig. 14(a). The LC array can be corrected by using perspective correction algorithm described in [38], as shown in Fig. 14(b).

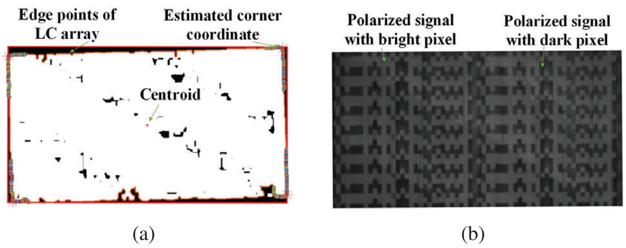


Fig. 14: The distortion image is corrected with corner coordinates. (a) Four corner coordinates are estimated by calculating the maximum distance from the centroid to edge points of LC array. (b) The final corrected image of polarized signals.

D. Demodulation with Pixel Intensity

The final step is to demodulate the polarization packets using the corrected image shown in Fig. 14(b). First, we mesh the image based on the regular arrangement of the LC array. The number of grid cells is equal to the number of bits in a polarization packet, and the size of the grid cell can be calculated from the number of cells. Then, grid cells are divided into groups. Each group contains eight cells and represents one byte of polarization packet. We perform binary processing on each group and calculate the proportion of black pixels in every cell. For each cell, if the number of black pixels exceeds half of the number of all pixels, it is considered to represent bit ‘0’; otherwise the cell represents bit ‘1’. With the above process, we are able to correctly demodulate LED signals and polarized signals from hybrid signals.

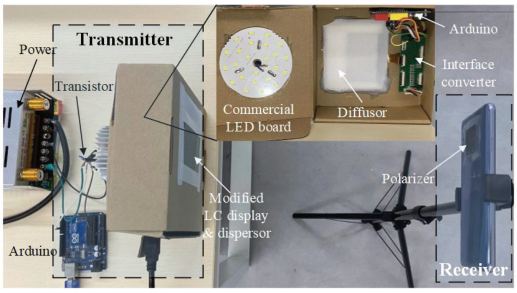


Fig. 15: Experiment setup.

V. Evaluation

In this section, we evaluate the performance of the hybrid modulation in real scenarios.

A. Experiment Settings

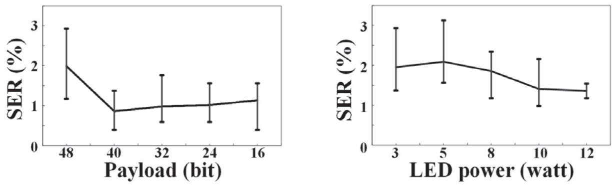
The testbed setting of our hybrid modulation scheme is shown in Fig. 15. We build the transmitter with a commercial LED board and a modified LC display that is inexpensive [18] and easy to deploy. We remove the upper polarizer from the commercial LC display to use as our LC array. Moreover, we adopt a polarizer around the LC array with 45° against the polarized light for corner positioning. A dispersor is attached to the LC display to highlight this polarizer. We adopt Arduino UNO as microcontroller and FQPF12N60C transistor ($0.3) to drive the COTS illumination LED board (voltage: 40 V, current: 0.3 A, diameter: 85 mm, $1.5). A diffusor is placed in front of the LED. The LC display is driven by an Arduino UNO. The data is segmented in a Raspberry Pi and distributed to LED and LC.

A commercial smartphone HUAWEI Mate 30 is used as the receiver. We set the exposure time to 1/8000 seconds and the frame rate as 30 fps. The resolution of camera is 1920×1080. We use auto-focus of camera introduced in [27]. A polarizer is attached to the camera [18], [19].

Each LED packet in a frame contains a header with 2 bits and a payload with 5 bytes. Note that, the last three frames in one hybrid modulation time (5 frames) use 4B6B coding which has $2/3$ coding efficiency. Every 5 frames in a hybrid modulation time have 20 bytes of LED packets. The polarization packet is composed of 256 bytes. Every four pixels of the LC display represent a bit. A 128×64 LC display contains 256 bytes. In summary, 276 bytes can be carried in 5 frames. We capture 10 sessions in the following experiments, and each session contains packets with 300 frames. We evaluate the performance of the hybrid modulation scheme with Packet Error Rate (PER) [40], Symbol Error Rate (SER) [26] and throughput with maximum, minimum and average values. The PER is applied for LED signal evaluation and the SER is used for polarized signal evaluation. All experiments are performed in an office environment with ambient light of 420 lux.

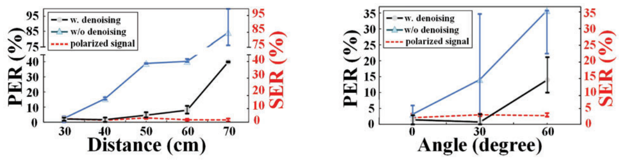
B. Impact of LED Parameter on Polarization

In this section, we study the performance of polarization communication with different experiment settings of LED.



(a) SER vs. Payload. (b) SER vs. LED power.

Fig. 16: SER of the polarized signal under different LED parameters. (a) SER varies with bit number in payload of LED packet. (b) SER varies with LED power.



(a) PER and SER vs. Distance. (b) PER and SER vs. Angle.

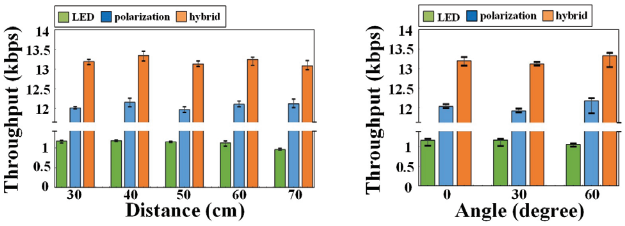
Fig. 17: PER and SER of hybrid modulation under different experiment settings. (a) PER and SER varies with distance between LED and camera. (b) PER and SER varies with view angle.

Width of band. As described in Sec.III-C, the polarized signal is recovered by splicing two LED packets adapting SRZI coding. The width of the LED band in these packets may impact the result of splicing image. To vary the width of bands, we adjust the payload in the LED packet with different bit numbers. The width of band can be expressed as $W_b = W_p/(P + H)$, where W_p is the length of a single LED packet, P and H are the bit numbers in the payload and the header, respectively. We vary the bit number from 48 to 16. The bit number of the relatively long payload is consistent with that described in [26]. Although it is able to set shorter payload, this will significantly reduce the data rate of the LED signal. We calculate the average, maximum and minimum value of the SER in 10 sessions. Figure. 16(a) reports the SER of the received polarized signal under various bit numbers in payload. We can see that the polarized signal has a lower SER when the bit number of payload is less than 40 bits. In the following, we fix the payload of 40 bits.

Power of LED. Another factor that may affect polarization communication is the power of the LED. The polarized signal transmission is empowered by the light of the LED. Low luminance of LED will result in weak polarized signal strength, which may increase SER. Thus, we vary the LED power from 3 to 12 watts. SER results of the polarized signal are shown in Fig. 16(b). SER becomes lower as the LED power increases. Overall, SER decreases insignificantly. We set the LED power to 12 watts in the following experiments.

C. Channel Property under Hybrid Modulation

We study the channel property of LED signal and polarized signal under hybrid modulation in this section.



(a) Throughput vs. Distance. (b) Throughput vs. Angle.

Fig. 18: Throughput of hybrid modulation under various experiment settings. (a) Throughput varies with distance between LED and camera. (b) Throughput varies with view angle.

Distance. We change the distance between the LED and the smartphone camera from 30 cm to 70 cm. Figure. 17(a) reports PER and SER of LED signals and polarized signals with the increase of distance. The PER of the LED signal is significantly reduced by denoising the signal as described in Sec. IV-A. In addition, the performance of LED communication degrades with increasing distance. However, the performance of polarization communication remains almost unchanged. The reason behind is that the ambient light reduces the SNR of LED signal with the increase of distance while the polarized signal is almost unaffected by ambient light due to the function of auto focus and optical zoom of the camera.

View angle. By fixing the communication distance to 30 cm, we examine PER and SER by varying the view angle of camera from 0 to 60 degrees. We define the angle of the camera directly in front of the LED to be 0 degrees. As shown in Fig. 17(b), the change in view angle degrades the performance of the LED communication, while the SER of polarized signal remains almost unchanged. This is because we correct the perspective distortion caused by the shift of view angle of camera in Sec. IV-C. A larger view angle (e.g. 60 degrees) may exceed the irradiance angle of the LED [41], resulting in lower light intensity which leads high PER of LED signal.

D. Throughput Evaluations

We evaluate the throughput of the hybrid modulation at different distances and view angles in this section. We average the data rate every 300 frames to get a throughput of 10 sections. The denoised LED signal is used in this section.

Distance. As in the study of transmission distance in Sec. V-C, the data rate of LED signal is influenced by distance, while the polarized signal is not. As shown in Fig. 18(a), the throughput of the LED signal decreases with an increasing distance, while the throughput of the polarized signal does not change substantially. The throughput of polarized signal (tens of kbps) significantly improves the overall data rate. In general, the average throughput of hybrid signal is 13.2 kbps, and the peak throughput can up to 13.45 kbps.

View angle. We then assess the throughput with different view angles of camera. Fig. 18(b) shows the throughput of different view angles. The data rate of polarized signal is still stable rather than LED signal with the change of view angle. The hybrid signal can reach an average throughput up to 13.3 kbps (with a peak value of 13.4 kbps). This throughput satisfies the requirement of minimum data rate (11.67 kbps) in the IEEE standard for VLC [1]. All results demonstrate the robustness of hybrid modulation in real-world scenarios.

VI. Discussion

Our hybrid modulation scheme has a great security advantage and potential for throughput expansion. Benefiting from the additional polarization dimension, it provides a new direction for increasing the data rate of LED-Camera VLC.

Security analysis. VLC has always been considered to be more secure [1], [3], [42] than radio frequency (RF) communication due to its limited communication range. However, recent work [43] shows that VLC is at risk of data leakage through the RF side channel in the non-line-of-sight (NLOS) region, mainly due to the high current (large than 20 mA) and voltage of the wire connecting to the LED. The data of VLC is recovered by sniffing the change of magnetic field caused by the LED wire. By contrast with LED, polarized signal is modulated with LC which is driven by low level voltage (less than 5 V) and small current (less than 1 mA). Therefore, polarized signals reinforce the security of VLC.

Effect of the LC array. In this paper, we only explore fixed-size LC array to modulate polarized light, i.e., the number of LC cells is constant. The throughput of polarized signal increases linearly with the number of LC cells [18]. Therefore, it is entirely possible to use a larger LC array to achieve a higher data rate, which may actually drive the hybrid modulation scheme to achieve Mbps level throughput. Furthermore, using high order modulation [29] for LC can also improve the throughput.

VII. Conclusion

Aiming to break the limit of data rate in LED-Camera VLC, we propose to use polarization dimension to enlarge the amount of data carried in frames. A hybrid modulation scheme is designed to enable hybrid signal transmission of LED and polarization. The scheme is implemented with COTS devices and achieves reliable communication with a throughput up to 13.4 kbps. The key idea is to increase the amount of data in frames by using polarized signals. In addition, to handle channel conflict between LED signal and polarized signal, we design a packet structure of hybrid modulation and propose a SRZI coding to overcome the conflict. We also develop a corner positioning method with a pixel-free way to correct the perspective distortion caused by shift of view angle. We demonstrate the reliable and promising performance of our hybrid modulation scheme through extensive experiments.

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