Long distance non-line-of-sight (NLOS) optical camera communication based on the barker code pilot

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***Abstract*—In this paper, we propose a data decoding algorithm based on the Barker code pilot (DDBP). The scheme meets the requirements of the 7% forward error correction threshold of the NLOS channel at 5 m.**

***Index Terms*—Visible light communication (VLC), Optical camera communication (OCC), Non-line-of-sight (NLOS), blooming effect.**

I. Introduction

Visible light communication (VLC) has garnered significant attention in recent years [1]–[4], particularly with the rise of smart devices. Mobile phones with complementary metal-oxide-semiconductor (CMOS) image sensors have become indispensable in people's daily lives. Optical camera communication (OCC), which is being considered as a standardization candidate for issues in IEEE 802.15.7r1, has unique advantages in receiver characteristics [5].

According to the propagation mode of light, OCC channel modeling can be divided into two modes: the line-of-sight (LOS) link and the non-line-of-sight (NLOS) link. In the LOS link, the light source directly transmits the light signal to the image sensor without any obstacles [6]. However, when the user is moving, direct light signals to the mobile phone camera may be obstructed by objects, resulting in interruptions to LOS-OCC. Nonetheless, since the surfaces of objects reflect light signals, the mobile phone camera can still receive reflected light signals, enabling NLOS-OCC to be carried out [7].

Despite the progress made in OCC systems, there are still pressing issues that need to be addressed.

1) The transmission distance of the OCC system is limited by the hardware CMOS image sensor, and the current OCC transmission distance is generally 2 m [8], [9]. With the distance increasing, the bright and dark fringes are difficult to distinguish, which brings a challenge to information reception. Therefore, solving the problem of fringes blurring is necessary to ensure longer transmission distance.
2) Internal electrical equipment noise, photon overflow and external ambient light [10] will affect the transmission signal in OCC system, thus leading to the blurring of the fringes at the receiver. How to alleviate these interference is a critical issue.

To ensure decoding reliability, digital image processing technology should be embedded in decoding. To address the problem of fringes blurring, this paper proposes a data decoding algorithm based on the Barker code pilots (DDBP) to extract incomplete bright and dark fringes and distinguish them with fuzzy boundaries and increase the communication distance. In this paper, we consider NLOS channel using the white LED and commercial camera as transmitter and receiver respectively. Furthermore, we use the white wall as the reflective surface. The experimental results show that our scheme can meet the requirements of the 7% forward error correction (FEC) threshold, which BER is 3.8×10^{-3}, at 5 m with Bradley adaptive threshold algorithm [11]. Moreover, the data rate can achieve 3 kb/s, and the required illumination is only 14 lx.

II. Algorithm and experiment

A. Algorithm

As shown in Fig. 1, the symbol period of '1' and '0' codes are same at the transmitter (Tx). However, at the receiver (Rx), the photons of the bright fringes tend to overflow to the edge of the dark fringes, causing internal interference between the fringes. As a result, the number of pixels of the bright band is larger than that of the dark band. To address these issues, this paper proposes a data decoding algorithm based on the Barker code pilot.

In the Tx, we utilize the 8-bit Barker code ('11010010') as the pilot signal. By analyzing the auto-correlation characteristics of the Barker code sequence, we can locate the head of the data. Additionally, the unique design of the code, which includes ’101’ and ’010’ segments, enables us to determine the number of pixels that correspond to 1-bit light or dark fringe, respectively. We assume that the 1-bit light fringe corresponds to p_L pixels and the 1-bit dark fringe corresponds to p_B pixels. Therefore, in this demodulation, each 1-bit fringe corresponds to p pixels.

$$p = \frac{p_L + p_B}{2} \tag{1}$$

Our demodulation process utilizes the DDBP scheme, which effectively resolves the issue of photon overflow. By averaging the number of pixels of 1-bit bright and 1-bit dark fringes, we can determine the number of pixels that correspond to a single bit fringe, and subsequently apply compensation to reduce system error rates.

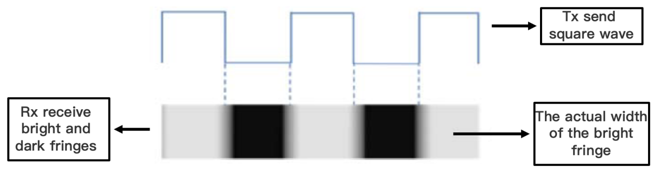

Fig. 1. Internal interference between the fringes.

B. Experiment

The experimental process and concept of the NLOS OCC system are illustrated in Fig. 2. A field-programmable gate array (FPGA) (Xilinx Altera EP4CE6F17C8 model) is connected to an amplification circuit that boosts the signal. The LED output power is 9.8 W and the data rate is 3 kb/s. The signal travels through optical channels and is captured by the CMOS camera of a HUAWEI P50 Pro smartphone, which has a resolution of 3840 x 2160 pixels and a frame rate of 60 fps. The ISO and exposure time of the phone are set to 6400 and 1/4,000 s, respectively. The transmitted data frame consists of an 8-bit preamble of “10110010” and a 40-bit payload. During the NLOS demonstration, the distance between the LED and the reflective surface (d1) increases from 1 m to 6 m, and the distance between the reflective surface and the mobile phone (d2) is fixed at 50 cm.

The insets of Fig. 2 demonstrate the flow chart of the rolling shutter pattern demodulation. The first step is to convert the color pattern into a grayscale version. Then we perform histogram equalization to enhance the contrast of the light and dark fringes. Since each row of pixels records the same data signal due to the short exposure time, we only need to select a suitable row matrix [9] of grayscale values from the image that is free from blooming regions and contains all the necessary information for signal demodulation. Our developed DDBP method is then applied to eliminate the internal interference between the fringes. Finally, we distinguish the data logic and evaluate the performance of our DDBP scheme against a simple background in the NLOS channel by comparing it with the conventional polynomial fitting method and the Bradley adaptive scheme [11].

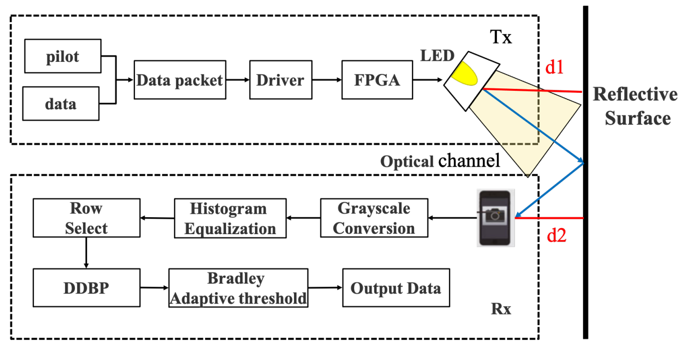

Fig. 2. The experimental block diagram of the OCC system using NLOS link.

In the proof-of-concept experiment, the total length of the optical path changes by moving the LED’s position. After capturing a video of the optical signal and uploading it to the computer, the MATLAB program processes each frame of the video. Our proposed demodulation algorithm restores bright and dark fringes taken at the Rx to logic 1 and logic 0. Additionally, the mobile application performs the demodulation and decoding procedure equally well.

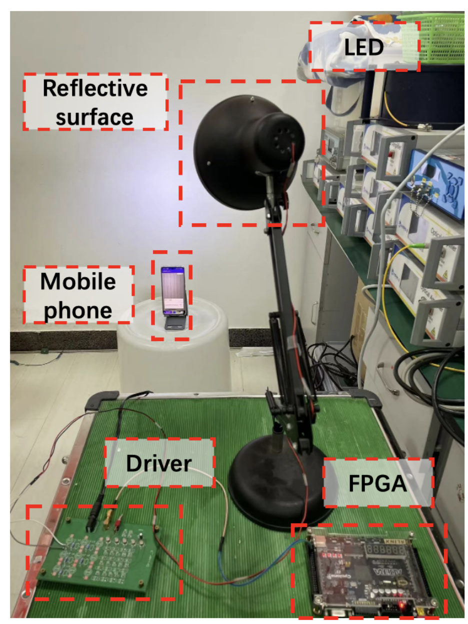

Fig. 3. Experiment setup of the NLOS OCC system.

The multiple experiments are conducted under different conditions using the experimental setup shown in Fig. 3, in which each experiment collected about a 10 seconds video for BER calculation of the system.

Fig. 4 depicts the BER curves versus distance with different scheme for NLOS transmission. It can be seen that even against a completely plain white background, both the polynomial fitting method and the Bradley adaptive scheme

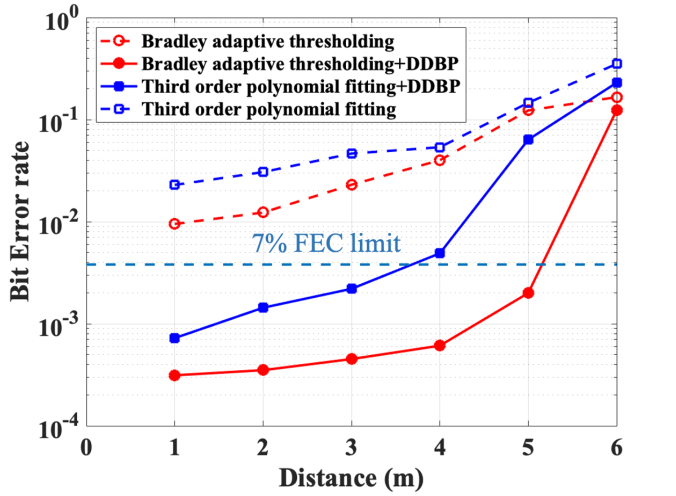

Fig. 4. BER performance at different transmission distances.

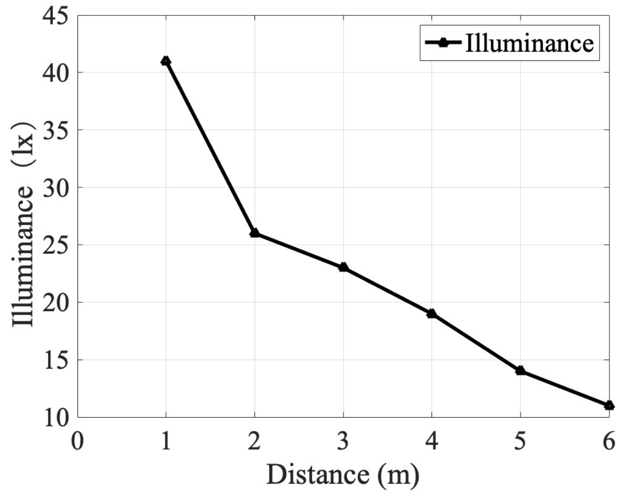

Fig. 5. Illuminances at different transmission distances.

do not work well when the distance gets farther and farther. Besides, the illumination drops off sharply with distance in our experiments, as presented in Fig. 5, severely affecting the accuracy of the Bradley adaptive scheme. It can also be observed that, if we use the DDBP scheme to preprocess the video frames before using these two methods, the BER performance can be further improved.

At the same time, we find that only use the third order polynomial fitting scheme or the Bradley adaptive scheme cannot achieve the 7% FEC threshold even if the distance is only 1 m. However, the BER significantly reduces with the help of DDBP scheme. At close-range communication, the BERs ($10^{-4} \sim 10^{-3}$) of all the threshold methods are small enough to meet communication requirements after using the DDBP scheme. The third order polynomial fitting scheme with our proposed scheme reaches the 7% FEC threshold at 3 m and 23 lx. The proposed scheme with the Bradley adaptive scheme stands out at low illumination of 14 lx with the BER of 2.0×10^{-3} that meets the 7% FEC threshold requirement under simple reflective background at 5 m distance. Moreover, the data rate of long-distance communication can achieve 3 kb/s.

Conclusion

In this paper, we proposed DDBP scheme to enhance the performance of OCC. We first described our procedure of row matrix selection, including grayscale conversion, histogram equalization, row selected. Then, the selected row matrix of grayscale values is processed by signal processing algorithms to be used for demodulation, including reducing the internal interference between the fringes by proposed DDBP scheme, and comparing the performance of the third order polynomial fitting scheme and the bradley adaptive scheme for thresholding. Finally, we evaluate the BER of NLOS-OCC system for different distances ranging from 1 m to 6 m. The data rate of long-distance communication can achieve 3 kb/s. Our experimental results demonstrate that the proposed DDBP scheme significantly improves the system's BER performance.

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