The First Study of MIMO Scheme within Rolling-shutter Based Optical Camera Communications

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***Abstract*— In this paper, we propose the first study of MIMO (multiple-input multiple-output) scheme using a simplified design of MIMO transmitter (Tx) based on grouping of light-emitting diodes (LED) within an array for flicker-free transmission in optical camera based communications (OCC) link. We carried out an initial experimental investigation of indoor static downlink OCC using a Raspberry Pi camera as the receiver with rolling-shutter capturing mode and a 7.2 × 7.2 cm² small 64-neopixel LED array as the Tx. The initial study suggests that, despite the small area of the display, communication links from 20 up to 60 cm can be established.**

Keywords—Optical camera communications, internet of things, multiple-input multiple-output, rolling shutter, light-emitting diodes

I. Introduction

Emerging optical wireless communication (OWC) technologies such as visible light communications (VLC), camera-based VLC or optical camera communications (OCC) and free-space optical communications [1]–[3] have been considered to take part in future generation wireless networks implemented within internet of things (IoT). VLC using light-emitting diode (LED) transmitter (Tx) has a low deployment cost since the existing LED lamps within the infrastructures can be used for both communication and illumination (lighting). On the other hand, cameras within the pervasive consumer electronics and are being explored to deliver extra capabilities beyond traditional imaging. The new generation smart devices have built-in complementary metal-oxide-semiconductor (CMOS) cameras that can be used to capture photos and videos. OCC is studied within the context of OWC and considered as part of the IEEE 802.15.7rl standard [3]. OCC implemented within IoT environments provide multiple functionalities such as illumination (lighting), data communications, localization and motion detection (MD) [3] – [5]. These OCC functionalities can be considered to develop IoT based network applications within smart environments such as home, office, hospitals, surveillance, etc., that include device-to-device communications [6], mobile atto-cells [7], vehicle-to-everything (V2X), etc., [8] – [10]. OCC deployed with LED and photodetector (PD) arrays used in the form of multiple pixels can offer massive MIMO (multiple-input multiple-output) capabilities for both indoor and outdoor in line of sight (LOS) and non-LOS (NLOS) environments within IoT applications [11, 12]. However, the data rate in OCC is limited due to the capture speed of the camera.

Using high-speed cameras can increase the data rate in OCC. However, the camera capture speed is a physical parameter of the sensor that is related to hardware electronics and the graphics processor speed. Therefore, hardware modification on the camera is necessary to change the capture speed. Authors in [13] proposed the MIMO transmission using an array of red, green and blue (RGB) LEDs for data transmission. A color-intensity modulation (CIM) MIMO scheme providing data throughput of 126.72 kbps was achieved by applying 256-CIM to 192 LEDs for data transmission at a transmission frequency of 82.5 Hz (still lower for flicker-free links) and a 330 frames per second (fps) mobile phone camera [14]. On the other side, within IoT environments, reliable, robust and flicker-free communication is of more importance as compared to high-speed communication links. Therefore, IoT based smart environments can be satisfied with just a few kbps links to transmit the required short information within the devices. To this end, a flicker-free screen-camera communication method using the interframe difference to improve the bit error rate (BER) along with increasing transmission distance (L) was proposed in [15]. Investigation of some energy harvesting for MIMO VLC schemes using repetition coding (RC), spatial multiplexing (SMP) and a modified version of spatial modulation (SM) was performed in [16].

The rolling shutter (RS) capturing effect of a CMOS camera within OCC can be a promising approach [17] – [20] to provide flicker-free OCC links as well as increase the data rate. The CMOS-RS camera sequentially integrates light on every pixel and then it operates as a scanning function [17]. Therefore, the rolling shutter camera operates at high-speed of row-by-row sequentially scanning and then exposing the on/off states of LED blinking in the received images. The data rate of 5.7 kbps was achieved using blooming mitigation and extinction ratio enhancement on the received RS pattern in [18]. The RS acquisition scheme for high-rate of 22 kbps and flicker-free screen-to-camera communication using spatially adaptive embedding was studied in [19].

Over the past few years, multiple neopixels have been embedded as a part of electronic devices such as screen displays in home automation, advertising, televisions, human interfaces, etc. [20]. Therefore, they can be used as a part of transmitter units to define IoT based MIMO-OCC links within smart environments. In this paper, we show the simplified design of MIMO-OCC Tx that uses 64-neopixel LEDs distributed in 8 × 8 array as Tx and a Raspberry Pi camera module (RaspiCam) as the receiver (Rx). The Tx unit is divided into 8 different groups with 8 LEDs in each group in order to increase the data throughput and achieve flicker-free transmission environment. On the Rx side, RaspiCam employed with 1920 × 1080 pixels resolution and 30 frames per second (fps) frame rate, capture the LED array with RS mode at shutter speed (SS) of 200 µs and L of 20 and 60 cm.

The remainder of the paper is organized as follows: Section II describes the MIMO scheme for IoT within OCC, while Section III shows the experiment results and analysis. Conclusions and future scope of the proposed scheme are mentioned in Section IV.

II. MIMO SCHEME FOR IOT WITHIN OCC

A. *MIMO-OCC Tx unit*

Figure 1 shows the assembly of Tx unit composed of 64-neopixel array with 8 × 8 small chip-LEDs, LED grouping grid with an outer edge thickness of 1 cm to separate the LED groups and an opaline methacrylate LED diffuser. As shown in Fig. 1, the size of the LED array is 7.2 cm × 7.2 cm. The size of each chip-LED is 5 mm × 5 mm, which is smaller than the distance between each LED within chips (brown chips in Fig. 1), 9 mm. Therefore, the light from each LED is captured by the camera as a distinct image.

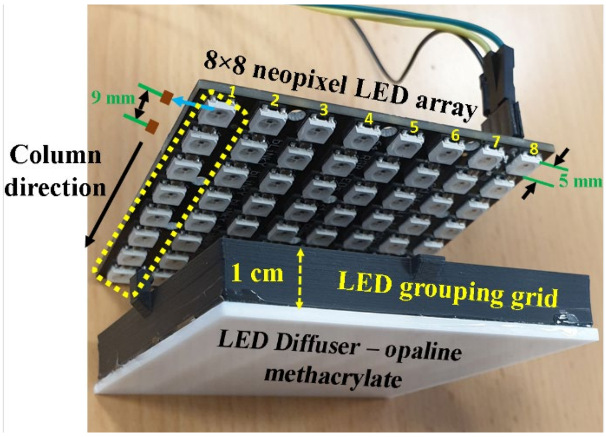

Fig. 1. Tx unit: the assembly of the Tx unit.

As shown in Fig. 1, the designed LED grouping grid divides the 64-neopixel array into 8 different groups (numbered from 1 to 8) in the column direction (highlighted in the yellow rectangle) with 8 LEDs in each group. Therefore, we can have 8 different data streams within a single neopixel LED array. The opaline methacrylate LED diffuser is commonly used LED diffuser material. The commercial use of this diffuser is described in [21].

B. *System overview of MIMO-OCC*

Figure 2 illustrates the flow diagram of the proposed MIMO-OCC based on the utilization of 64-neopixel Tx unit and a RS RaspiCam as Rx. For data modulation, we have employed non-return to zero (NRZ) on-off keying (OOK) modulation format (commonly used in OCC). The proposed scheme is an initial study to test the upper bounds of the system using the proposed Tx unit, therefore we assume perfect synchronization and clean line-of-sight transmission. The data is generated at the Arduino unit and mapped to the LED addresses. The Tx transmits the NRZ-OOK modulated signal at frequency f_s calculated as:

$$f_s = (t_{\text{bit}})^{-1}, \tag{1}$$

where the t_{bit} is the 1-bit time of each neopixel chip. The minimum t_{bit} due to Arduino hardware limitation is 2.5 ms in order to have flicker-free transmission, therefore the value of f_s was fixed to 400 Hz.

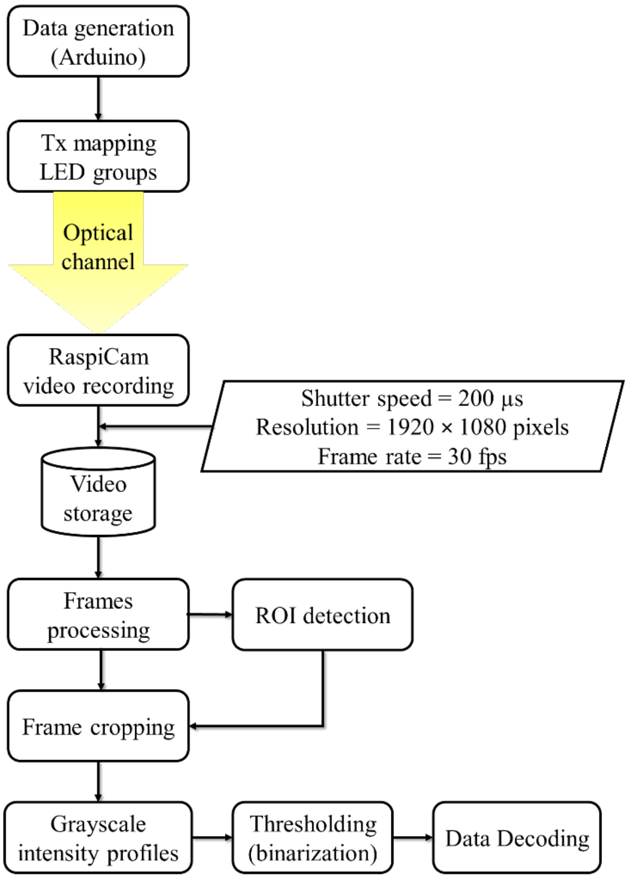

Fig. 2. OCC data processing flowchart.

The RaspiCam used as the Rx captures the video stream (divided into image frames for processing) of the NRZ-OOK modulated Tx and store them for its post-processing. To perform faster processing, a region of interest (ROI) which is a small image with only the Tx's signal information is extracted in the first step [5, 22]. The coordinates from the boundaries of the ROI are used to crop the rest of the images. The cropped images are then converted to grayscale images to retrieve the intensity profile. The threshold level is set based on the image intensity profile to perform binarization of the data frames and applied to the remaining frames for decoding the data bits.

Figure 3 illustrates the RS acquisition mode of the RaspiCam. The majority of CMOS based imaging sensors for digital cameras operate in RS acquisition mode. In this mode, the sensor scans row-by-row of pixels (line wise) the entire image, with a delay between each row [23]. In this mode, the pixel sensors within the camera continuously integrate the light that falls on their surface. Every row of pixels is exposed during a t_{exposure} time.

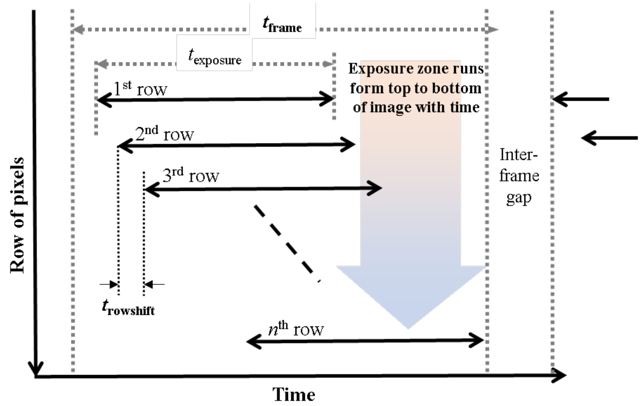

Fig. 3. RS acquisition mode.

While capturing in RS mode, each row starts with some delay which causes the row shift, $t_{rowshift}$. The time of each frame, t_{frame} is given as:

$$t_{\text{frame}} \leq N_{\text{row}} \times t_{\text{rowshift}} + t_{\text{exposure}}, \tag{2}$$

where the value of N_{row} is 1080 pixels based on 1920 × 1080 pixels resolution, $t_{exposure}$ exposure time of n^{th} row that is negligible value as compared to the full frame scanning duration. The maximum number of visible bits in each group, $N_{visible}$, in one frame is given as:

$$N_{\text{visible}} = \left\lfloor \frac{t_{\text{frame}}}{t_{\text{bit}}} \right\rfloor. \tag{3}$$

Based on the maximum number of visible bits from (3), the data transmission rate, R_d is given as:

$$R_d = N_{\text{groups}} \left(\frac{1}{t_{bit}} \right), \tag{4}$$

where N_{groups} is the number of LED groups in Tx unit (see Fig. 1).

To calculate and check the upper bound of the system we transmitted some known bit streams in NRZ-OOK format through respective LED groups as shown in Fig. 4. Note that, all the 8 LEDs in each group transmits the same data as assigned.

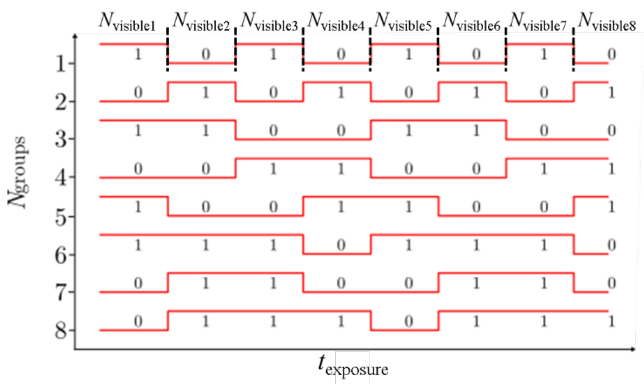

Fig. 4. Transmitted data bit stream through respective LED group.

The advantage of dividing LED groups provides the provision of capturing multiple bits in a single exposure time as shown in Fig. 4. The bits in groups 1 and 2 show inversion (group 1 transmitting 0 bit at the same time group 2 transmitting 1 bit), this is intentionally set to check the synchronization of each LED group transmitting the same number of bits but different sequences of 1's and 0's.

III. Experiment Results and Discussion

The experimental setup for the MIMO-OCC scheme demonstration is shown in Fig. 5. The Tx unit was controlled using an Arduino Uno board, which is an opensource microcontroller board that is operated via ATmega328 [24]. The data stream of 64 bits (8-bits each group as shown in Fig. 4) was generated in the Arduino software domain and was mapped to each LED (i.e., address) using Arduino Uno board.

Fig. 5. Experiment setup of MIMO-OCC scheme.

The experiment parameters are listed in Table I. The camera used for the setup is the Raspberry Pi official camera, model PiCamera V2, which is based on the Sony IMX219 sensor [25]. For the demonstration of the proposed study, experiments were performed at L of 20 and 60 cm and SS of 200 µs (see Fig. 2 for camera settings). Figure 5 also shows the captured Tx unit showing RS based captured data over 8 different LED groups on the Raspberry display screen.

TABLE I. Parameters of the Experiment Setup

Parameter	Value
RaspiCam resolution	1920 × 1080 pixels
RaspiCam chip size	5.09 mm (H) × 4.930 mm (W) Diagonal: 4.60 mm
Raspberry display size	7" (diagonally)
Raspberry display resolution	800 × 400 pixels
t_{bit}	2.5 ms
f_s	400 Hz
Frame rate	30 fps
N_{row}	1080 pixels
N_{groups}	8 LED groups
t_{frame}	0.216 ms
SS	200 µs
R_d	3.2 kbps
L	20 and 60 cm

Figure 6 provides examples of the captured image frames at L of 20 and 60 cm and SS of 200 µs. The dotted yellow box represents the ROI that fills only the captured Tx within the full image frame. The clear and sharp distinction between data lines can be seen at SS of 200 µs. It can also be seen that, at L of 20 and 60 cm, 8 and 2 full bits can be captured within each LED group. As well as, perfect synchronization can be seen in every group transmitting different bits.

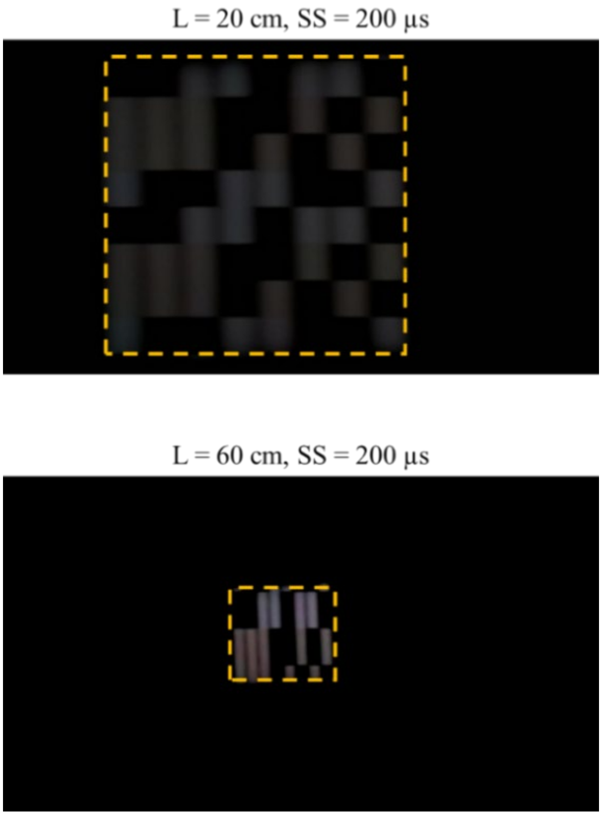

Fig. 6. Captured images of the received bits for L of 20 and 60 cm and SS of 200 µs.

IV. Conclusion and Future Scope

This paper demonstrates the proof of concept implementation of a RS acquisition based camera capturing in OCC links including a simple design of modified Tx unit. The implementation of MIMO-OCC link with the proposed Tx unit was experimentally evaluated. The idea of LED grouping on the Tx side can help to increase the data throughput as well as to implement flicker-free OCC link. The OCC link quality will be further evaluated in terms of image quality metric of signal-to-noise ratio SNR at increasing values of L and SS. The effect of image saturation due to an increase in SS can be studied further with the evaluation of SNR metric.

Use of large illuminating surface (large size) Tx's can increase the data throughput with an increase in $N_{visible}$ and N_{groups} as well as increase the link spans. The performance of the proposed MIMO-OCC link quality will be further studied to evaluate BER. Using different Tx configurations can also pave the way for the implementation of mobility and multiuser schemes in IoT based smart home environments.

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