Algorithm for bit identification in RSE-based camera VLC links impaired by blooming

Felipe Adalberto Farinelli, Sergio Luiz Stevan Jr. and Alexandre de Almeida Prado Pohl

***Abstract*— A method to identify bits impaired by the blooming effect in a LED - CMOS camera visible light communication link that uses the rolling shutter effect (RSE) is described. The algorithm is based on OOK modulation, Manchester coding and a geometric procedure to interpret the received information. Tests executed to measure the algorithm performance revealed an average run-time of 2.5 ms, showing that the proposed technique has a good potential to be employed in short distance identification and positioning systems.**

***Keywords*— CMOS camera, LED, Manchester coding, VLC.**

I. INTRODUCTION

Currently, two types of receivers are employed in Visible Light Communication (VLC) links: photodiodes (PD) and camera sensors [1]. Photodiodes are mostly used in Optical Wireless Communications (OWCs) systems. On the other hand, due to smartphone ascension, handheld cameras are part of people's environment and, in the context of VLC, they can be employed as receivers in Optical Camera Communications (OCC) systems, considering them as a photodiode array. High and low-speed cameras can be employed in communication links, but low-speed cameras are low-cost and therefore have found wider use [2]. Even so, many works using camera communication via smartphone have been reported, as in [3], [4], [5], [6].

VLC employing mobile phones has gained considerable attention since they are widespread and offer an embedded light source (Light Emitting Diode, LED) that acts as a transmitter and a complementary-metal-oxide-semiconductor (CMOS) camera that functions as a receiver [7]. With the advance in mobile networks (5G and 6G), camera-based communication has become a reality for the implementation of several applications pushing ahead the existence of Internet-of-Things (IoT) [8].

However, the present data rates are still low since the camera frame rate is limited to 30/60 fps. In order to overcome such limitation, the camera rolling shutter effect (RSE) has been proposed as it enables rates higher than the frame rates, as demonstrated by Chow [9], Liang *et al* [10] in a wavelength division multiplexing (WDM) link with a red-green-blue (RGB) LED, whose scheme provided 2.88 kbit/s at a distance of less than 10 cm, or shown by Ndjiongue *et al* [11], in whose work color-shift-keying modulation is employed in link distances up to 1 m. To enhance faster transmissions, the use of algorithms that improve image processing is also a must [6].

When cameras are utilized as receivers, some problems could appear, like the image blooming (due to glare effect), which occurs due to the overflow of charge from the saturated pixels into the camera neighboring pixels, when the received signal is strong. To tackle this issue, Ohira [12] used, for instance, an algorithm based on Gaussian filters in a multiple-input-multiple-output (MIMO) system.

In this perspective, [13] and [14] present a roof-of-concept experimental setup for visible light communication using mobile-phone image sensor. [14] describe a comparison of algorithms of the thresholding schemes, in special a third-order polynomial curve fitting. A mobile-phone CMOS image sensor (Samsung GT-S7500), with 480 x 640 pixels resolution and 28 frame/second frame rate was used to transmit a 32-bit payload. The measured processing time in our mobile phone is 14.29 ms 0.896 kbit/s. In [15] was proposed an entropy thresholding algorithm, including maximum entropy thresholding and minimum cross entropy thresholding. Data rate of 5760 bit/s can be achieved. They reported a net data rate of 5760 bit/s was achieved using the 96-bit payload. [16] presents a study of the performance of various LED light luminaires (bulb, panel light, downlight and tube) for VLC systems that use the rolling shutter mechanism of CMOS sensors. They concluded that the key of the VLC link using CMOS includes not only the decoding algorithm, but also the LED light source, being downlight the more indicated. They also demonstrated to use of the contrast limited adaptive histogram equalization to extend the transmission distance and mitigate the influence of the background noise. Moreover, in [17], the authors reported an analysis of the low-density parity check (LDPC) code in the Optical Camera Communications to overcome burst error, and proposed a Contrast limited adaptive histogram equalization (CLAHE) to increase the contrast of stripes in the captured picture and reduce the complex techniques for decoding techniques due to the blooming effect. The experiments were performed using only the center part of an image frame. The authors affirmed that this scheme extended the transmission distance by 0.5m.

In this panorama, this work is proposed roof-of-concept experimental setup of a simple demodulation technique of Manchester coding, which employs an algorithm at the receiver side, which is based on a geometric procedure that enables the identification and recovery of the bit sequence in systems obfuscated by the power of the LED transmitter at short distances, improving the accuracy of the decoding

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process.

The manuscript is structured in four sections. Section II presents the materials and methods used, section III, the results obtained followed by their discussion and finally, section IV presents the conclusion of the work.

II. Materials and Methods

The system described in this work comprises of a 12V modified LED E27 light bulb (12 W Cool White (6.500K) with 1060 Lumens LED Bulb), shown in Fig. 1, controlled by an ESP32 and driven by a transistorized buffer system as transmitter (TX). In this case, a smartphone (Xiaomi Redmi Note 9s) was used. It had a Quad main camera and the Maximum analog sensitivity (ISO) was 3200). In addition, a smartphone with a camera or a software configurable 5MP camera (Raspcam) can be used as receiver (RX) and to provide images to a Raspberry Pi module, responsible to processing the data. The transmitter is aligned with the receiver in a line-of-sight configuration and separated by a distance of 15 cm. The short distance and the high power of the transmitter, consisting of 10 LED sources distributed over the printed circuit board (PCB), causes the blooming effect in the camera-based receiver [18]. As our main focus in this work is the data recognition algorithm, we initially used an image obtained by a camera from a smartphone to deliver the image to a raspberry module to evaluate the algorithm.

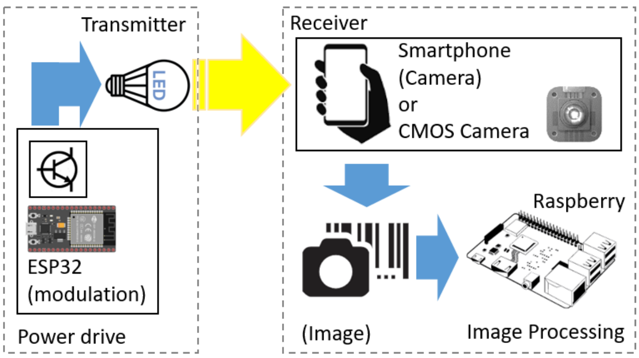

Fig. 1. VLC-CAM link

The usage of Manchester coding with OOK modulation in low data VLC systems is a technique for preventing perceivable flickering (light intensity fluctuation caused by the modulation technique) and has been used in several works [19] and [20]. In this encoding technique, a “high” bit is changed to “high-to-low” transition and a “low” bit is changed to “low-to-high” transition in a bit time interval [9]. Fig. 2 shows this technique, exemplifying the ASCII code 65_{10} (character A), which in binary is represented by ”01000001_2”, and encoded by Manchester as ”0110010101010110”.

Fig. 3 shows the frame obtained by the camera, which is the result of the RSE, since all photodiodes of the CMOS camera are sampled vertically, column by column, creating black and white stripes. The image of Fig. 3 is taken considering the transmission of a packet containing a 5-bit header followed by a 16-bit data field using OOK modulation and Manchester coding at a frequency of 1 kHz. The frame delimitation starts on its header and ends in the next header, assuming that the header sequence ’01110’ is not coded in Manchester, which makes it easily detectable by the receiver because the sequence of 3 or more equal bits means an error in Manchester-encoded data.

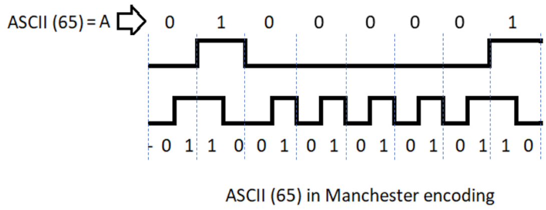

Fig. 2. Example of ASCII data encoded in Manchester code.

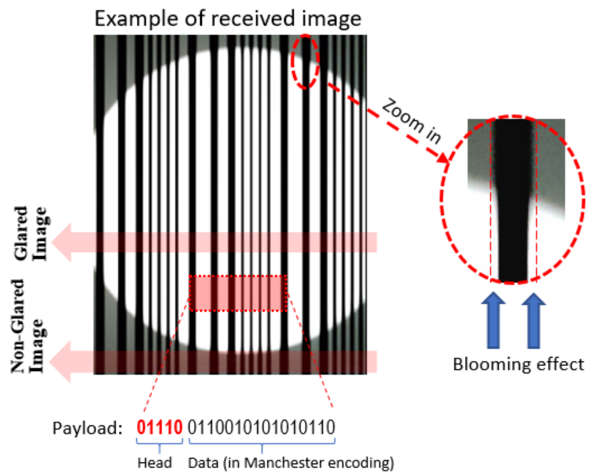

Fig. 3. Captured frame where the blooming effect (glare) is clearly visible.

To obtain the image in Fig. 3, the steps indicated in Fig. 4 are followed. The image-processing is done offline in one frame, after the image has been acquired.

The procedure includes the conversion of the raw image obtained by the camera from the smartphone, with ISO 600 and 1/4000 shutter-speed, to a gray-scale pattern, transforming the image in an one-dimensional matrix of the same resolution, defined as 640x480 pixels. After the conversion to gray-scale, a data array containing the values of all image columns is obtained, as shown in Fig. 5 (a) and (b), respectively. The challenge here is to find where there is a sequence of two consecutive ones (’11’) or zeros (’00’) in the Manchester coding, since their pattern in the receiver are different.

To solve this problem, an algorithm is proposed based on the search for the average intensity values in each column. Through interpolation over the points of the data array using a third degree polynomial fit, it is possible to compare whether the average level of a column is above or below the value derived from the polynomial curve for that column, thus allowing to generate a positive value, indicating that it is a bit 1, or a negative value, indicating that it is a bit 0.

Thus, assuming that a straight line connects the corresponding pairs of vertical lines, where x and y are midpoints and x_0 and y_0 are the straight lines starting points, we obtain the

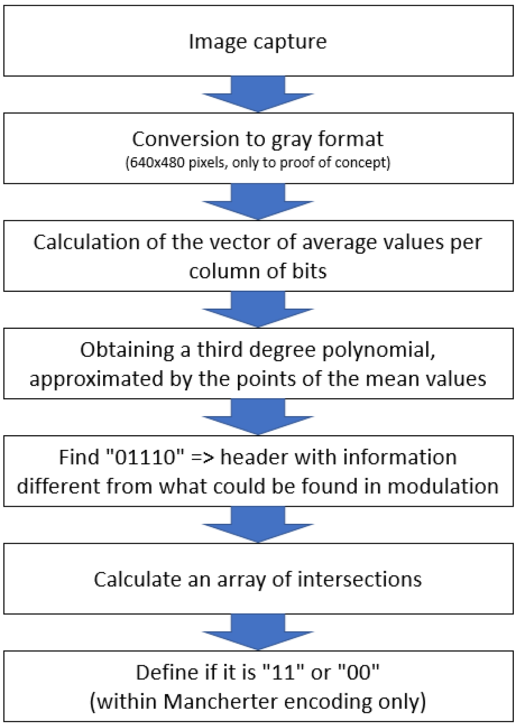

Fig. 4. Flowchart with the processing steps for decoding data in Manchester code.

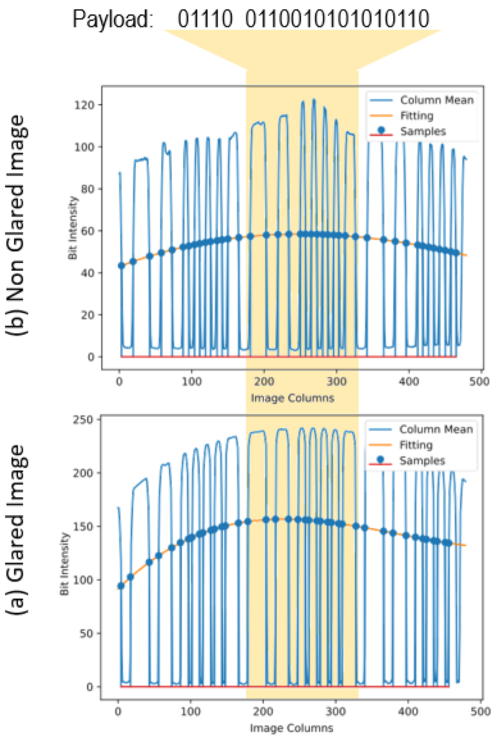

Fig. 5. Captured frame processed, based on the glare image (a) and the non-glared image (b).

line slope m, as given by (1).

$$m = \frac{x - x_0}{y - y_0} \tag{1}$$

Considering that x_0 is the same in both arrays, as shown in Fig. 6 (b) and (c), and that $y_{0(a)}$ and $y_{0(b)}$ are the mean and polynomial fitting data points of each array, respectively, it is possible to calculate the coordinates x_d and y_d, respectively, as given by (2) and (3) and highlighted in Fig. 6 (c). Note that m_a and m_b are the slopes of curves between each pixel of the mean data array and of the calculated fitting data array, respectively.

$$x_d = \frac{(m_b.x_0) - y_{0(b)} - m_a.x_0 + y_{0(a)}}{m_a - m_b} \tag{2}$$

$$y_d = (-m_a.x_0) + y_{0(a)} + m_a.x_d \tag{3}$$

After applying (2) and (3), it is possible to determine where the intersection of both curves lies by comparing the coordinates $\mathbf{x_d}$ and $\mathbf{x_0}$, considering a security margin (x_{mg}) as shown in (4).

$$x_p = |x_0 - x_d| \leq x_{mg} \tag{4}$$

In according to the margin utilized in (4), some points may be repeated or very close to each other. To avoid it, these points could be removed from coordinates by applying another margin, x_q, but now referent to its neighborhood.

An array with the coordinates of the intersections x_e is used to estimate the intervals between consecutive coordinates, and, later, compare them with the average value of the interval between different bits, as expressed in (5). Subsequently, the average value x_{mind} is calculated to identify the midpoint of a range of equal bits, as given in x_p (6).

$$x_e(k) = |x_p(k) - x_p(k-1)| \geq x_q \tag{5}$$

$$x_{mid}(k) = \frac{|x_e(k+1) - x_e(k)|}{2} + x_e(k) \tag{6}$$

where k is a integer referring to the position of the column in the acquired image.

With all the coordinates where the intersections between the mean array and the polynomial fittings are, the header may be found. The header will be the unique part of the data, which will contain more than three consecutive '1' bit. Now, the data may be located and interpreted.

For the bloom-impaired image (glare effect) in analysis, all bits midpoints may be found by applying the (6). Each interval of the $y_{0(a)}$ that is above $y_{0(b)}$ is considered as bit '0', as well as the opposite condition is '1'.

After, the distance between bit midpoints and its respective borders are obtained by (7) and (8). This result will be considered to find where are sequences of two consecutive bits or just one, in according to Manchester coding. Note that the glare effect is not quantified, bits '0' and '1' must be processed individually and the header is not included in this calculus, due to its nonconformity to the coding.

$$d_0(k) = (y_{0(b)}(x_{mid}) < y_{0(a)}(x_{mid})).x_e(k) - x_{mid}(k) \tag{7}$$

$$d_1(k) = (y_{0(b)}(x_{mid}) \geq y_{0(a)}(x_{mid})).x_e(k) - x_{mid}(k) \tag{8}$$

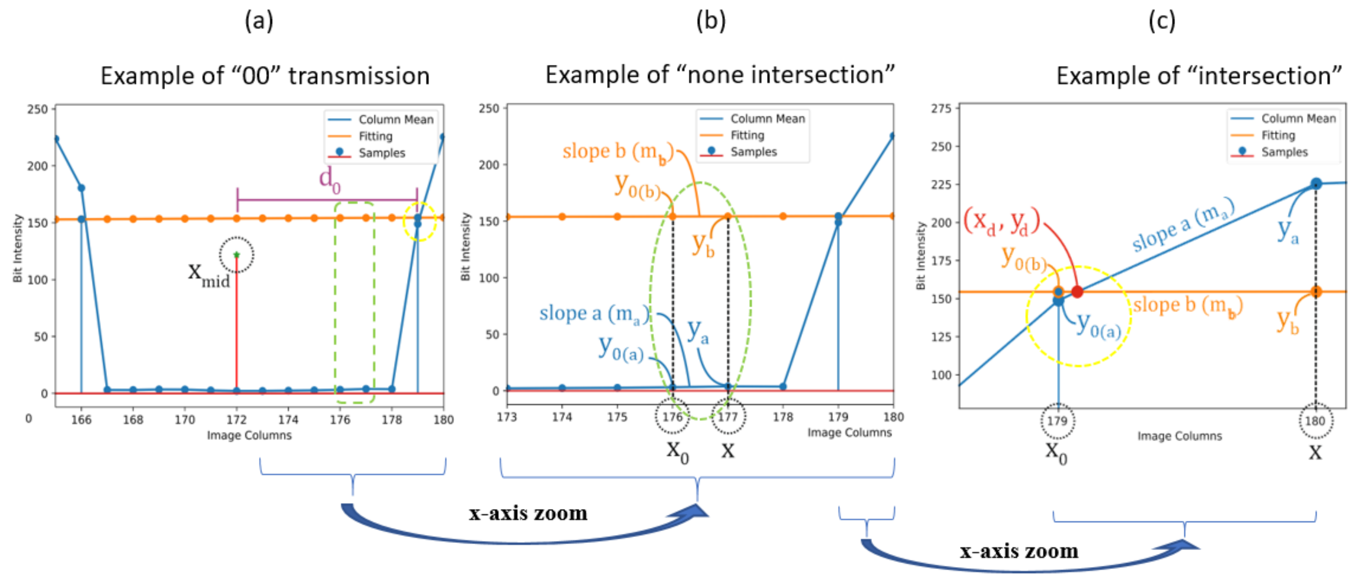

Fig. 6. (a)example of two consecutive zeros (00); (b) example where none intersection is found by the algorithm; and (c) example where the intersection of the column mean and fitting is found.

An example for d_0 is presented in Fig. 6 (a). Note that the x array coordinate, x_d, is one unit right shifted on both equations. Such a result is considered in order to find where two consecutive bits, or just one, lie in the sequence, according to the Manchester coding. Note that the blooming effect is not quantified, bits ’0’ and ’1’ must be processed individually and the header is not included in this calculus since it is not coded in Manchester.

With the calculated distances for bits ’0’ and ’1’ given above, it is possible to determine the mean value of each one. According to its mean, each interval greater than it represents a sequence of two bits, otherwise, just one. Since the midpoint position is known, then an array of data is found, which is now independent of the bloom affecting the system. So, the last step is to decode the signal and convert it to ASCII. We note that this algorithm works well in Manchester coding, since any sequence of more than two equal bits means an error and it carries its own clock at the expense of bandwidth.

III. Results

Data reception was done using the bit sequence shown in Fig. 3, which consists of the header (’01110’, uncoded information) and the character ’A’ encoded in Manchester, ensuring that a complete frame is available for decoding. Applying the algorithm, the intersection points were found, where the bit length varies according to its type, being ’1’ larger than ’0’ when the blooming effect impairs the glared region of the image (see the right side sketch in Fig. 3) .

The obtained sequence after decoding is $\mathbf{01000001_2}$ which is interpreted as 65_{10}, the corresponding code of character "A"in ASCII table. The time for capturing a frame by the camera was measured as 13.8 ms, remaining 2.9 ms eventually for executing the whole algorithm, from image conversion, to gray-scale pattern to Manchester decoding, when the camera operates at the rate of 60 frames per second (fps). The same test was repeated 100 times in order to measure its run-time, which resulted in 2.5 ms average for the execution proving that it is possible to execute this algorithm in real-time.

All tests were done using the same captured frame for to evaluate the algorithm execution time and estimate the maximum bit-rate in a future real-time link, without, in this first step, considering the bit error rate (BER).

Considering a payload of 21 bits per frame and a camera capturing at 60 fps, a link of 1.26 kb/s may be established. This bit-rate is sufficient for some applications where communication speed is not primordial, like identification and positioning systems. Once the glare effect was filtered and the signal could be decoded in the receiver, it can be considered that the algorithm fulfilled its objective.

IV. Conclusion

We describe a geometric method to identify bits in RSE-based camera communication links impaired by the blooming effect. The proposed algorithm use midpoints between lines of captured images, which represent the black and white stripes corresponding to the transmitted bit sequence. The system consists of a half-duplex VLC link (LED - /CAM) using Manchester encoding. As proof of concept, a sequence of 21 bits is transmitted and correctly recovered at the receiver in an off-line process. Considering the transmission of 21 bits per frame, as demonstrated in this work, and the camera operating at 60 fps, a link of 1.26 kbps can be established. However, by adjusting the system parameters, the 21-bit packet can be transmitted at least three times within the same frame, which means that one frame could carry up to 63 bits, communicating at a rate of 3.78 kbps. To achieve higher transmission rates we can still increase the camera resolution and also the transmitter frequency; however, there is a limiting combination of distance, resolution and the blooming effect that should be obeyed. The run-time for processing the data is low enough and fits into the time window of a camera operating at 60 fps. Such bit-rate is sufficient in applications where communication transmission rate is not primordial at short distances, such as in identification and positioning systems.

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Referências

[1] Xianbo Li, Babar Hussain, Jian Kang, Hoi Sing Kwok, and C. Patrick Yue. Smart led display-vlc system with a pd-based/camera-based receiver for nfc applications. *IEEE Photonics Journal*, 11(1):1–8, 2019.

[2] Nasir Saeed, Shuaishuai Guo, Ki-Hong Park, Tareq Y. Al-Naffouri, and Mohamed-Slim Alouini. Optical camera communications: Survey, use cases, challenges, and future trends. *Physical Communication*, 37:100900, 2019.

[3] Jing He, Zhongwei Jiang, Jin Shi, Yudong Zhou, and Jing He. A novel column matrix selection scheme for vlc system with mobile phone camera. *IEEE Photonics Technology Letters*, 31(2):149–152, 2019.

[4] Chi-Wai Chow, Chung-Yen Chen, and Shih-Hao Chen. Enhancement of signal performance in led visible light communications using mobile phone camera. *IEEE Photonics Journal*, 7(5):1–7, 2015.

[5] Zhenshan Zhang, Tiantian Zhang, Ji Zhou, Yaojun Qiao, Aiying Yang, and Yueming Lu. Performance enhancement scheme for mobile-phone based vlc using moving exponent average algorithm. *IEEE Photonics Journal*, 9(2):1–7, 2017.

[6] Ke-Ling Hsu, Chi-Wai Chow, Yang Liu, Yu-Chun Wu, Chong-You Hong, Xin-Lan Liao, Kun-Hsien Lin, and Yi-Yuan Chen. Rolling-shutter-effect camera-based visible light communication using rgb channel separation and an artificial neural network. *Opt. Express*, 28(26):39956–39962, Dec 2020.

[7] Shlomi Arnon, editor. *Visible Light Communication*. Cambridge University Press, Cambridge, 2015.

[8] Harald Haas, Liang Yin, Cheng Chen, Stefan Videv, Damian Parol, Enrique Poves, Hamada Alshaer, and Mohamed Sufyan Islim. Introduction to indoor networking concepts and challenges in lifi. *J. Opt. Commun. Netw.*, 12(2):A190–A203, Feb 2020.

[9] Chi-Wai Chow, Chung-Yen Chen, and Shih-Hao Chen. Visible light communication using mobile-phone camera with data rate higher than frame rate. *Opt. Express*, 23(20):26080–26085, Oct 2015.

[10] Kevin Liang, Chi-Wai Chow, and Yang Liu. RGB visible light communication using mobile-phone camera and multi-input multi-output. *Optics Express*, 24(9):9383, May 2016.

[11] A.R. Ndjiongue, H.C. Ferreira, and A.J. Han Vinck. Segmental analysis of the transmission in CSK systems based on the Euclidean distance. In *AFRICON 2015*, pages 1–5, Addis Ababa, September 2015. IEEE.

[12] Yuki Ohira, Shintaro Arai, Tomohiro Yendo, Takaya Yamazato, Hiraku Okada, Toshiaki Fujii, and Koji Kamakura. Novel Demodulation Scheme Based on Blurred Images for Image-Sensor-Based Visible Light Communication. In *2015 IEEE Globecom Workshops (GC Wkshps)*, pages 1–6, San Diego, CA, USA, December 2015. IEEE.

[13] Han Liu and Fanshu Ma. Design of visible light communication transceiver system based on intelligent terminal. In *2021 IEEE 6th Optoelectronics Global Conference (OGC)*, pages 77–81, 2021.

[14] Yang Liu, Chi-Wai Chow, Kevin Liang, Hung-Yu Chen, Chin-Wei Hsu, Chung-Yen Chen, and Shih-Hao Chen. Comparison of thresholding schemes for visible light communication using mobile-phone image sensor. *Optics express*, 24(3):1973–1978, 2016.

[15] Kevin Liang, Chi-Wai Chow, Yang Liu, and Chien-Hung Yeh. Thresholding schemes for visible light communications with cmos camera using entropy-based algorithms. *Optics express*, 24(22):25641–25646, 2016.

[16] Weipeng Guan, Yuxiang Wu, Canyu Xie, Liangtao Fang, Xiaowei Liu, and Yingcong Chen. Performance analysis and enhancement for visible light communication using cmos sensors. *Optics Communications*, 410:531–551, 2018.

[17] Duy Thong Nguyen and Youngil Park. Performance enhancement of optical camera communication system using optical camera communication coding and region-of-interest detection. *IET Optoelectronics*, 15(6):255–263, 2021.

[18] Ajit Kumar and S. K. Ghorai. Effect of multipath reflection on ber performance of indoor mimo-vlc system. *Optical and Quantum Electronics*, 50(11):388, Oct 2018.

[19] Shuai Li, Ashish Pandharipande, and Frans M. J. Willems. Two-way visible light communication and illumination with leds. *IEEE Transactions on Communications*, 65(2):740–750, 2017.

[20] Klaas Minne Van Der Zwaag, Marianne Pontara Marinho, Wesley Da Silva Costa, Francisco De Assis Souza Dos Santos, Teodiano Freire Bastos-Filho, Helder R. O. Rocha, Marcelo E. V. Segatto, and Jair A. L. Silva. A manchester-ook visible light communication system for patient monitoring in intensive care units. *IEEE Access*, 9:104217–104226, 2021.