Boosting Optical Camera Communication via 2D Rolling Blocks

Xiao Zhang, Griffin Klevering, James Mariani, Li Xiao, Matt W. Mutka
Michigan State University, Department of Computer Science and Engineering, MI, East Lansing
{zhan1387, kleveri2, mariani4}msu.edu, lxiao@cse.msu.edu, mutka@msu.edu

***Abstract*—Optical Camera Communication (OCC) appears as a promising technology to provide secure and pervasive wireless services with users' daily smart devices. Rolling shutter based modulations can improve the frequency response of the camera. This paper introduces a 2D Rolling Block (2DRB) based OCC modulation to use un-exploited spatial diversity to improve OCC's data rate for real-world applications. 2DRB outperforms traditional 1D strip based modulations. Using our 2DRB prototype with commercial devices, we show a significant data rate enhancement. We also discuss one promising real-world use case: indoor office integrated lighting and communication.**

I. Introduction

Recent studies reveal that OWC (optical wireless communication) can provide reliable connections through Line of Sight (LoS) for secure communication as well as providing great potential of spatial multiplexing. Specifically, camera based OWC, termed as Optical Camera Communication (**OCC**) [3]–[12] attracts attention from both academia and industry thanks to pervasive smart devices such as smartphones, dash cams, and security cameras. Unlike a single-pixel photo diode, cameras need greater processing and readout time for light perceptions [13], [14]. Thus the frequency response of commercial cameras are only *tens of Hz* frame rate and *several kHz* of rolling shutter rate. This severely reduces the data speed and makes the camera-based receiver an OCC systems' bottleneck [15]. It is desirable to improve the OCC's data rate via the exploration of other un-exploited modulation diversities.

In this paper, a 2D Rolling Block (2DRB) based OCC modulation framework is introduced. This framework discovers and models spatial diversity to embed additional bits into a strip symbol. Additional bits per symbol with a larger symbol distance in each modulation diversity (e.g., brightness, color) help build a robust and higher-rate OCC system. Many researchers made attempts to embed additional bits within one optical symbol (i.e., high order modulation). However, their approaches embed data within one-fold diversity and therefore decrease symbol distance, such as CASK [1] with brightness in Yang's work and color [2] in Hu's work. These approaches only consider data embedding in **1D rolling strips** and do not consider 2D spatial diversity in optical imaging. The proposed 2DRB is practical due to its design with low orders in each diversity for robust decoding and diverse modulation diversities including temporal (i.e., brightness and color) and spatial diversities for improved data rate.

II. Problem Formulation

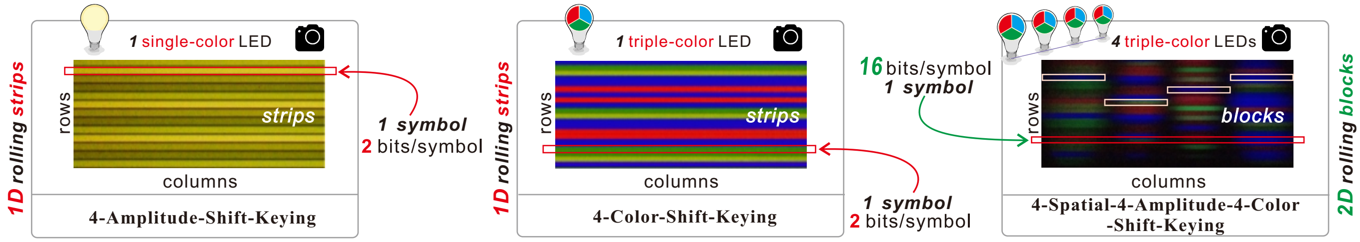
There are two types of OCC: (1) **LCD-OCC** using liquid crystal screen (tens of Hz frequency response) as the transmitter and adopting frame rate level (tens of Hz) for the camera's perception, (2) **LED-OCC** using LED (hundreds of KHz frequency response) as the transmitter and adopting rolling shutter rate level (tens of KHz) for the camera's perception. The **LCD-OCC** captures images frame by frame and subsequently decodes the embedded data, such as a QR code, in that frame. In contrast to **LCD-OCC**, the **LED-OCC** makes use of LEDs' faster On/Off switching rate rather than the low-speed liquid crystal, enabling it to record data with a faster shutter rate than the camera side frame rate. Our 2DRB modulation framework is designed for **LED-OCC** systems.

A **symbol** in LED-OCC is a specific rolling strip generated when the shutter rate is similar to the transmission frequency. Therefore, the temporal features such as different brightnesss or colors of the light source, which varies with time sequences, are recorded strip by strip vertically. The order in modulation is defined as the number of possible statuses for a modulation diversity. For example, if the specific rolling strip has 4 possible statuses in brightness, this rolling strip can denote 2 bits, as shown in Figure 1. To increase the data rate of LED-OCC, we can increase the order of the optical symbol or combine multiple modulation diversities simultaneously.

Existing LED-OCC systems do not consider spatial diversity in camera imaging, and treat the whole **1D rolling strips** for data embedding. Nevertheless, the image sensor of a camera consists of millions of pixels and can capture multiple light sources even in one specific rolling strip. Thus, the transmitter units at different horizontal locations with different brightness and colors can be recorded as **2D rolling blocks** instead of a single light source generated **1D rolling strips** for more data embedding in LED-OCC, as illustrated in Figure 1.

Our goal is to model horizontal spatial diversity and explore its proper combination with vertically recorded temporal diversity such as brightness and spectrum for increased embedded bits in one optical symbol. We should consider the manner of combination so we do not introduce additional overhead and sacrifice decoding robustness. We define O_b as the order of brightness diversity, O_c as the order of color diversity, and O_s as the order of the horizontal spatial diversity. We explore different combinations of these 3 diversities in data embedding. The choice of the order of each diversity can be

979-8-3503-9973-8/23/$31.00 © 2023 IEEE



(a) CASK (b) ColorBar (c) a 2DRB example

Fig. 1: The illustration of 2D rolling blocks spatial diversity in our proposed (c) a 2DRB example and its comparison with 1D rolling strips spatial diversity in state of the arts in OCC: (a) CASK [1] and (b) ColorBar [2].

0 or 4 to guarantee the low-order for robust decoding. For example, CASK in Figure 1 (a) adopts O_b as 4, O_c as 0, and O_s as 0. Similarly, ColorBar in Figure 1 (b) adopts O_b as 0, O_c as 4, and O_s as 0. As shown in Figure 1 (c), the horizontal spatial diversity can enable an optical symbol (i.e., a rolling strip) embed more bits even with low order in each diversity.

III. 2D Rolling Block Modulation

In this section, we describe how to model the spatial diversity in 2D rolling blocks and how to use the spatial diversity for embedding additional bits in a symbol.

A. Spatial Diversity Modeling

1) Camera shutter and spatial diversity in camera:

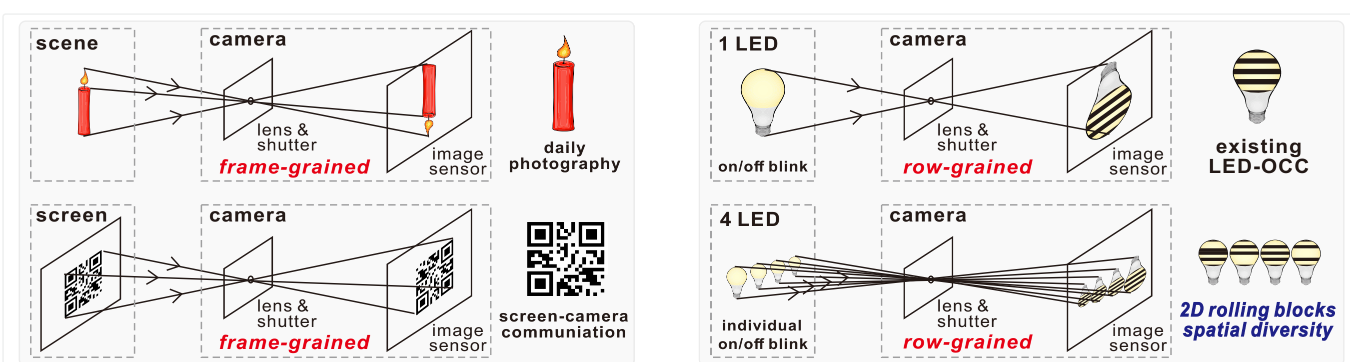
The shutter is an essential camera mechanism that controls a photographic film's effective exposure time. There are two shutter types: **(1) Global shutter** exposes the whole scene at the same time. Light sensors at each pixel collect light synchronously and are exposed at the same time. At the beginning of the exposure, all light sensors begin to collect the light, and cut off light sensing and collection at the end of the exposure. **(2)** Unlike a global shutter, the **rolling shutter** is implemented by exposing one row of pixels simultaneously and row by row generates an entire image.

Spatial diversity is generated by millions of pixels in 2D camera image sensors with multiple light sources shown in a camera's FOV. Each pixel or each cluster of pixels can record the optical features such as brightness and spectrum diversities of each light source shown in the FOV of a camera. Based on camera shutter types and the transmission frequency of LED sources, the spatial diversity can be classified into two categories: (1) with **frame-level** update speed, and (2) with **faster row-level** update.

2) Update with frame-level vs. row-level:

Frame-level updated spatial diversity. When one period of transmitted data from all light sources in FOV is emitted (synchronously or asynchronously) during the frame period and captured by cameras whatever the global shutter or rolling shutter, the captured frame will have no rolling strips and the transmitted data will be decoded at the frame level. For example, the existing screen-camera communication approaches [16] captures each frame as a full unit and subsequently decodes the embedded data. The UFSOOK [3] is also updated at the frame level although it repeats the data over several LEDs to provide spatial redundancy FEC.

Row-level updated spatial diversity. When one period of transmitted data from all light sources in the FOV is emitted synchronously during the rolling shutter period and captured by the rolling shutter camera, the captured frame has rolling strips and the transmitted data is decoded at the faster rolling-shutter level than the frame level. Compared with existing screen-camera communication and UFSOOK, which uses the low frame-level spatial diversity, the approaches that adopted rolling-shutter-level update speed are supposed to have a higher data rate due to its faster update rate. Nonetheless, these approaches (e.g., ColorBar, CASK [1], [2]) do not consider the spatial diversity and only exploit the **1D rolling strips** instead of the **2D rolling blocks** in our proposed 2DRB.



(a) spatial diversity at frame level update (b) spatial diversity at row level update

Fig. 2: Spatial diversity in camera imaging with frame / row level updates.

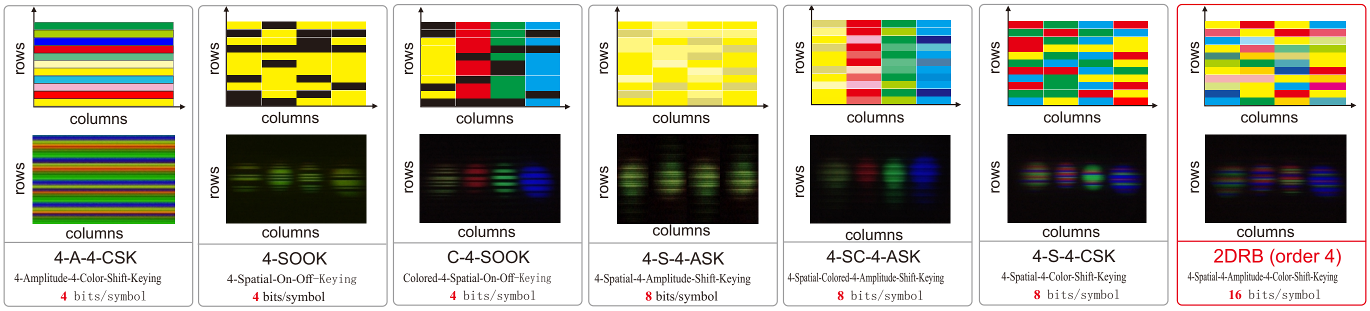


Fig. 3: The illustration and captured images of explored modulations.

B. Modulation Exploration

We explore 7 modulations for spatial, spectrum, and brightness diversities with 4 levels for each, as shown in Figure 3:

4-A-4-CSK: 4-amplitude-4-Color-Shift-Keying utilizes 4 colors with 4 amplitudes to denote 4 bits per symbol.

4-SOOK: 4-Spatial-On-Off-Keying adopts basic OOK at 4 different horizontal locations.

C-4-SOOK: Colored-4-Spatial-On-Off-Keying is similar to 4-SOOK with the same denoted bits. The only difference is that OOK has a different color at each location.

4-S-4-ASK: 4-Spatial-4-amplitude-Shift-Keying adopts 4-ASK at 4 locations, thus each symbol denotes 8 bits.

4-SC-4-ASK: 4-Spatial-Colored-4-Amplitude-Shift-Keying modulation adopts 4-ASK at 4 different horizontal locations. The only difference with 4-S-4-ASK is that each ASK has a different color instead of the same color.

4-S-4-CSK: 4-Spatial-4-Color-Shift-Keying adopts 4-CSK at 4 different locations, thus each symbol denotes 8 bits.

2DRB-order-4: 4-Spatial-4-Amplitude-4-Color-Shift-Keying uses 4-CSK combined with 4-ASK at four different locations, making each symbol denote 16 bits. This is a significant improvement on existing work [1], [2]. Ideally, the 2DRB protocol can extend to N-order and transmit the $\log_2(N \times N) \times N$ bits per rolling strip.

C. Undesired Flicker Mitigation.

Although we want cameras clearly to record multiple colors and levels of brightness for robust communication, we do not expect human eyes to sense the flickers in its concurrent lighting function. We avoid undesired flickers in two aspects. **(1) Fast transmission frequency.** 2DRB adopts transmission frequency at several to tens of KHz, which is faster than the response frequency of human eyes (i.e., 60Hz). **(2) Color/brightness Balanced Coding.** As presented in Figure 3, each transmission unit has 16 combinations of color and brightness (i.e, R1,R2,R3,R4,G1,G2,G3,G4,B1,B2,B3,B4,Y1, Y2,Y3,Y4) that are mapped to 16 different 4-bits segments (e.g, ‘0010’) with equal appearance possibility, preventing some color or brightness appearances at low frequencies that would have resulted in unwanted flickers.

Color Choice The top of Figure 4 shows that R+G generates Yellow, G+B generates Cyan and R+B generates Purple. The bottom-left of Figure 4 shows the measured hue values on our

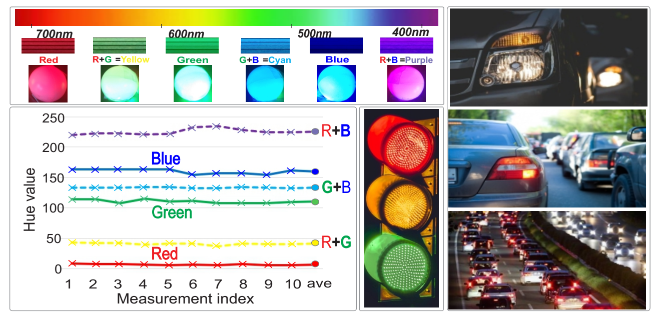


Fig. 4: Color choice of RGBY in spectrum diversity.

testbed. Cyan is too close to blue and green. Purple has the shortest wavelength out of these six colors, although having a wider hue gap than yellow. Thus we chose yellow as the 4^{th} color in addition to red, green and blue. Furthermore, yellow, red and green have longer wavelengths than cyan and purple, which makes them suitable for long distance propagation, the same as traffic lights and headlights.

IV. Performance Study

In this section, we introduce our 2DRB prototype and some results of performance study.

A. Implementation

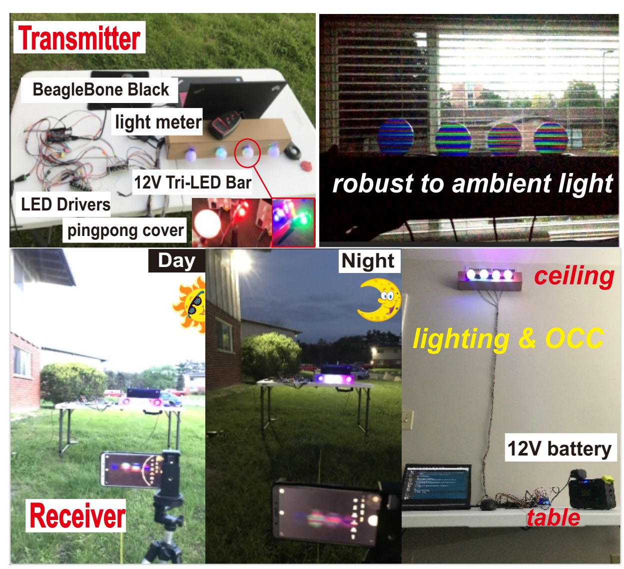


Fig. 5: 2DRB implementation and experiment scenarios.

Transmitter. We implement a low-cost 2DRB prototype, as shown in Figure 5. The transmitter consists of a BeagleBone Black as the micro control unit, self-implemented fast LED drivers with MOSFET transistors, and a 12V self-made high-power Tri-LED bar. The total cost is under **$100**. Each transmission unit consists of a red, a green, and a blue LED bulbs with white cover for better inner-unit light fusion.

Receiver. We use a commercial smartphone VIVO Y71A with an additional commercial magnifier. It performs decoding via OpenCV tools.

Use case. As shown in Figure 5, we put the LED bar on the ceiling while we set the receiver at the table to simulate the indoor office integrated lighting and communication enabled by 2DRB modulation both in day and night time.

B. Evaluation Results

Transmission Freq. (kHz)	1	2	3	4	5
4-ColorBar (kbps)	< 0.5	≈ 1	≈ 2	< 4	
4-CASK (kbps)			< 1	< 2	< 4
4-2DRB (kbps)	15. 2	30. 4	45. 6	60. 8	76

TABLE I: Performance comparison with the sate-of-the-art.

Comparison with Existing LED-OCC. Both hue and lightness maintain the necessary spacing for reliable decoding across a variety of transmission frequencies, distances, and ambient light. In comparison to previous high-order modulation techniques as the 16-ColorBar and 32-ColorBar, 2DRB achieves the SER (symbol error rate) reduction and the throughput improvement [1], [2]. As illustrated in Table I, the throughput achieved by 2DRB is more than 10 times of the same-order 4-ColorBar and 4-CASK modulations. When the transmission frequency is set to 5 kHz, the 2DRB of 4-order can achieve 76 kbps.

Transmission Dist.	0.5 m	1 m	1.5 m	2 m	ave
data rate (k bps)	147. 8	146. 4	145. 1	143	145. 6
Ambient Light Sett.	**day**	**night**	**artificial**	**ave**	
data rate (k bps)	146. 4	146. 7	143. 2	145. 4	

TABLE II: Evaluation results at indoor office setting.

Results of Indoor Use Case. We set the transmission frequency at 10 kHz and with a fixed lens setting. We set 4 different distances for indoor scenario: 0.5 m, 1 m, 1.5 m, and 2 m. The achieved data rate fell somewhat as the distance between the transmitter and the receiver increased, going from 148 Kbps at 0.5m to 143 Kbps at 2m, a difference of only 5 Kbps. Additionally, in order to research the impact of ambient light, we also perform studies during the day, at night, and in situations with artificial light sources (light provided by humans). Throughout the day, we maintain a fixed lens setting of 1 m. 2DRB reaches 146.4 Kbps, 146.7 Kbps, and 143.2 Kbps independently with no appreciable performance difference between the three settings, as shown in Table II.

V. Conclusion

In this paper, a spatial diversity model based 2D Rolling Block (2DRB) modulation framework is introduced. The modulation takes into account the spatial diversity in optical imaging and thus has the ability to embed more bits in each rolling strip as an optical symbol. We model the spatial diversity and combine it with low-order temporal diversities in brightness and colors in exploration. The commercial device based 2DRB prototype is implemented for performance study. The results demonstrate the potential of 2DRB as a promising modulation framework for the practical LED-OCC systems.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. CNS-2226888 and Grant No. CCF-2007159.

References

[1] Y. Yang and J. Luo, "Boosting the throughput of led-camera vlc via composite light emission," in *IEEE INFOCOM 2018-IEEE Conference on Computer Communications*. IEEE, 2018, pp. 315–323.

[2] P. Hu, P. H. Pathak, X. Feng, H. Fu, and P. Mohapatra, "Colorbars: Increasing data rate of led-to-camera communication using color shift keying," in *proceedings of the 11th ACM conference on Emerging Networking experiments and technologies*, 2015, pp. 1–13.

[3] "Ieee standard for local and metropolitan area networks–part 15.7: Short-range optical wireless communications," *IEEE Std 802.15.7-2018 (Revision of IEEE Std 802.15.7-2011)*, pp. 1–407, April 2019.

[4] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *IEEE Access*, vol. 6, pp. 9819–9840, 2018.

[5] X. Zhang, H. Guo, J. Mariani, and L. Xiao, "U-star: An underwater navigation system based on passive 3d optical identification tags," in *The 28th Annual International Conference on Mobile Computing and Networking*, 2022.

[6] X. Zhang and L. Xiao, "Effective subcarrier pairing for hybrid delivery in relay networks," in *2020 IEEE 17th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*. IEEE, 2020, pp. 238–246.

[7] ——, "Lighting extra data via owc dimming," in *Proceedings of the Student Workshop*, 2020, pp. 29–30.

[8] ——, "Rainbowrow: Fast optical camera communication," in *2020 IEEE 28th International Conference on Network Protocols (ICNP)*. IEEE, 2020, pp. 1–6.

[9] X. Zhang, G. Klevering, and L. Xiao, "Exploring rolling shutter effect for motion tracking with objective identification," in *Proceedings of the Twentieth ACM Conference on Embedded Networked Sensor Systems*, 2022, pp. 816–817.

[10] ——, "Posefly: On-site pose parsing of swarming drones via 4-in-1 optical camera communication," in *2023 IEEE 24th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, 2023, pp. 1–10.

[11] X. Zhang, G. Klevering, J. Wang, L. Xiao, and T. Li, "Rofin: 3d hand pose reconstructing via 2d rolling fingertips," *Proceedings of 21st ACM International Conference on Mobile Systems, Applications, and Services, conditionally accepted*, 2023.

[12] X. Zhang, G. Klevering, X. Lei, Y. Hu, L. Xiao, and T. Guanhua, "The security in optical wireless communication: A survey," *ACM Computing Surveys (CSUR)*, 2023.

[13] E. Ramadhani and G. Mahardika, "The technology of lifi: A brief introduction," in *IOP Conf. Series: Materials Science and Engineering*, vol. 3, no. 25, 2018, pp. 1–10.

[14] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is lifi?" *Journal of lightwave technology*, vol. 34, no. 6, pp. 1533–1544, 2015.

[15] S. Zhu, C. Zhang, and X. Zhang, "Automating visual privacy protection using a smart led," in *Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking*, 2017, pp. 329–342.

[16] K. Qian, Y. Lu, Z. Yang, K. Zhang, K. Huang, X. Cai, C. Wu, and Y. Liu, "Aircode: Hidden screen-camera communication on an invisible and inaudible dual channel." in *NSDI*, 2021, pp. 457–470.