# RainbowRow: Fast Optical Camera Communication

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***Abstract*—Thanks to the popularity of smartphones, optical camera communication (OCC) gains more and more attention from markets and research as one of the new internetworking architectures in the future. However, existing OCC modulations treat the signal from the transmitter as a single point light source, which sacrifices the spatial diversity and limits the data rate improvement. In this paper, we investigate the spatial diversity, a natural feature of camera imaging, and propose to combine spatial diversity with amplitude and spectrum diversities to boost the data rate of OCC to support high-speed applications. Based on preliminary experiments, we design and implement *RainbowRow*, a high-speed and robust OCC system. *RainbowRow* comprises a LED-based transmitter and a camera-based receiver, which is low-cost (*i.e.*, under $100), with a flexible communication range (*i.e.*, within 2 m), and high speed (*i.e.*, up to 40 Kbps). To validate the *RainbowRow* performance, we conduct experiments on LabVIEW based platforms in different scenarios. Results show that *RainbowRow* can robustly recognize the optical symbols with a symbol error rate (SER) less than 0.05 and approach 40 Kbps data rate in the range of 1 m, significant improvement from less than 10 Kbps in OCC state of the art.**

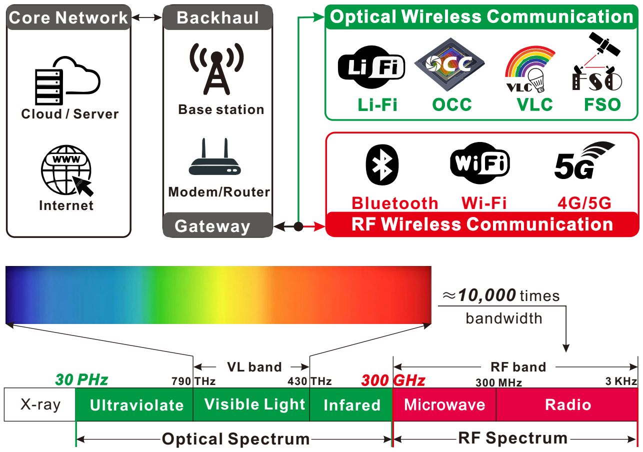

Fig. 1: Optical wireless communication and RF based wireless communication. Optical spectrum has broader bandwidth than RF spectrum.

## I. INTRODUCTION

Since new high-speed multimedia applications and services continue to emerge, higher requirements are put forward for wireless local area network (WLAN), wireless personal area network (WPAN), and high-speed cellular networks such as fifth-generation (5G) and beyond [1] [2]. Existing wireless infrastructures such as Wi-Fi are based on radio frequency (RF) and strictly regulated by local authorities. The RF spectrum is not sufficient for future massive high-speed wireless services, while the optical spectrum has more than 10, 000 times broader bandwidth, as shown in Fig.1. Light-emitting diodes (LED) with fast switching property make it possible for high-speed optical wireless communication (OWC). It offers reliable connections via LOS spread for secure communication and high-capacity networks [1] [3].

As one of OWC techniques, optical camera communication (OCC) has attracted more attention due to its low interference, low price, the popularity of smartphones with built-in cameras. However, developing a high-speed, low-cost, and practical OCC system as a NIPAA (New Internetworking Protocol Architectures and Algorithm) technique is still an open issue. Unlike single light sensor based OWC techniques such as LiFi [4] only adopt one photodiode (PD), the image sensor (IS) in a camera consists of millions of pixels (each pixel element can be treated as one PD). It requires more data processing and readout time for light sensations, such as the rolling shutter camera in commercial smartphones. Thus, it limits the data rate significantly at the receiver side even the LED-based transmitter has more than 1MHz transmission frequency [3].

Researchers have made many attempts to improve the OCC data rate. Yanbing [5] [6] investigated a high-order modulation, CASK (composite amplitude shift keying), which encodes data into different luminance levels. Pengfei [7] [8] proposed using CSK (color shift keying) in OCC as ColorBar, which encodes data into different colors. They achieved about 10s Kbps data rate for commercial smartphone-based OCC. However, these approaches only consider the grayscale difference (amplitude diversity) and color difference (spectrum diversity) in modulation for improved speed and ignore the spatial diversity of camera imaging.

In the IEEE OWC standard [9], it defines UFSOOK (undersampled frequency shift on-off keying) modulation for PHY IV of OWC. UFSOOK encodes bits as OOK symbols and utilizes the spatial feature of multiple LED sources and pixels on camera to achieve spatial redundancy FEC (forward error correction) to reduce errors in transmission. It inspires us to exploit the spatial diversity for improved data rate. To this end, we explore another dimension, the spatial diversity of camera imaging, and combine it with amplitude and spectrum diversities in our modulation *RainbowRow* to boost the data rate of the OCC system.

Our **contributions** can be summarized as follows:

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- We propose a novel insight into improving the OCC data rate by exploiting the spatial diversity of camera imaging. We find that the combination of spatial diversity with amplitude and spectrum diversities can be utilized for optical symbol modulation.
- We develop *RainbowRow*, a high-speed and robust OCC system which are low-cost and practical. We address the flicker and color overlapping challenges at the transmitter and develop a robust decoding algorithm for the commercial camera-based receiver.
- We evaluate the efficacy and reliability of *RainbowRow* under different communication scenarios. *RainbowRow* achieves less than 0.05 SER and up to 40 Kbps data rate in the range of 1 m, significant improvement from less than 10 Kbps in OCC state of the art.

## II. CONCEPTS AND PRELIMINARIES

### *A. Amplitude Diversity: Brightness and Grayscale*

Amplitude diversity means the grayscale difference. We can use PD (photodiode) or PR (photo resistance) to measure grayscale value, i.e., the intensity of the light emitting or reflecting from the light source or the objects. As Fig. 2 shows, different amounts of light can be reflected as different voltage or digital signals in the circuit. In OCC, a grayscale image is one in which each pixel's value is a single sample representing only an amount of light. It carries only intensity information. Grayscale images, a black-and-white or gray monochrome, are composed exclusively of shades of gray.

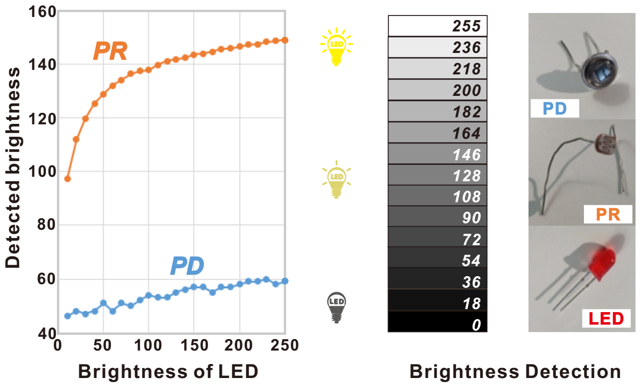

Fig. 2: Amplitude diversity generated by different brightness of LED and measured by light sensors as grayscale. Two light sensors PD and PR perform differently.

### *B. Spectrum Diversity: Color Generation and Detection*

At the transmitter, commercial Tri-LEDs are used to generate a variety of colors with a broad optical spectrum; this is called the RGB color model. **R**ed (700 nm), **G**reen (546.1nm), and **B**lue (435.8nm) are combined in various ways to reproduce other colors. In IEEE OWC standard [9], it defines color shift keying (CSK) modulation. The optical symbols are generated based on the points on the CSK constellation triangles. The CSK constellation is decided by combining selected three color bands, which can form a triangle on the xy color coordinates of CIE 1931 [10]. It increases the symbol space and distance than the same order amplitude shift keying (ASK) modulations. However, CSK modulation has a complicated and high requirement for control at the transmitter with additional overhead and cost. Also, it brings challenges of accurate symbol recognition for the receiver.

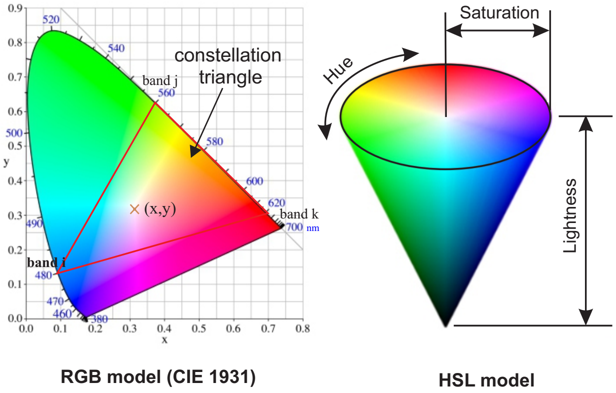

Fig. 3: Illustration of color generation principle (RGB) in Tri-LED and detection principle (HSL) via color filter.

Compared with the RGB model used for the color generation, the HSL model is more natural to describe colors and more popular for color recognition at the receiver, as shown in Fig.3. H stands for Hue, which corresponding to the red, orange, yellow, green, cyan, blue, violet, etc. Hue reflects changes and differences of colors more directly, which is the spectrum diversity of the optical wavelength. A beam of light may be composed of many different wavelengths of monochromatic light—the more kinds of wavelength, the higher S (Saturation) value. L stands for Lightness or Luminance, and it reflects the grayscale of the light. HSL model separates the brightness and color of the light, which are the amplitude and spectrum diversity separately.

### *C. Spatial Diversity: New Insight*

The shutter is the mechanism of a camera to control the effective exposure time of a photographic film. There are two kinds of shutters: global shutter and rolling shutter. The 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 at the end of the exposure, the light sensing and collection circuits are cut off. The whole sensed light values are then read as a photo. Unlike a global shutter, the rolling shutter is implemented by exposing one row of pixels simultaneously and in a row by row method to generate a whole photo. At the beginning of the exposure, the sensor scans line by line until all pixels are exposed. Of course, all the action is done in a very short time. Thus rolling shutter has a higher readout frequency compared with the global shutter.

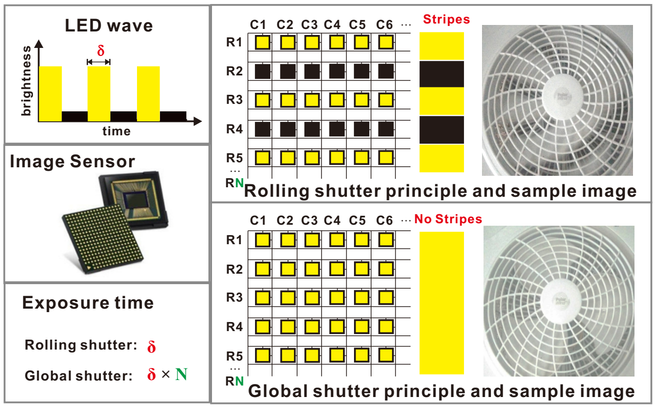

Fig. 4: Rolling shutter stripe effect and contrast with global shutter in camera imaging.

The rolling shutter helps the camera capture the light signal from the different time slots and represent them in one image orderly (row by row following the time sequence). When the light wave from the transmitter changes illuminance faster than the rolling shutter speed, there will appear the stripe effect [5], as shown in Fig.4. Thus, the optical signals and transmitted data in a period of time from the transmitter can be sequentially recorded on one image (frame), making it have faster demodulation ability than the global shutter. Existing rolling shutter based modulation methods treat each or multiple continuous rows of the captured image as one whole part then decode it. For example, CASK measures the average grayscale of pixels from one stripe (multiple continuous rows) and decode it as a symbol. ColorBar measures the R, G, and B values of one stripe and decodes it as one symbol.

However, each row comprises multiple pixels as well, which could record the multiple color or grayscale in a different part of pixels in this row. This spatial diversity on each row provides the possibility to boost the throughput further. In order to take advantage of the spatial diversity at the receiving end, spatially related coding and the modulation are required at the transmitting end. The transmitter should have significant multiple optical signals in different spatial locations.

## III. RAINBOWROW: HIGH-SPEED OCC

### A. *Diversity Combination: Principle and Benefit*

Based on the analysis and principle in Sec.II, we propose to combine amplitude diversity, spectrum diversity, and spatial diversity with improving the data rate of the OCC system, as shown in Fig. 5. The benefit of this combination is that we can eliminate the short symbol distance limitations for each diversity. We can employ the robust and proper range in each diversity for modulation separately. Let $A$ denotes the amplitude diversity, $S_1$ denotes the spectrum diversity and $S_2$ denotes the spatial diversity in each row. The bits encoded in each symbol $B$ can be represented as follows:

$$B = S_2 \times \log_2 (A \times S_1) \tag{1}$$

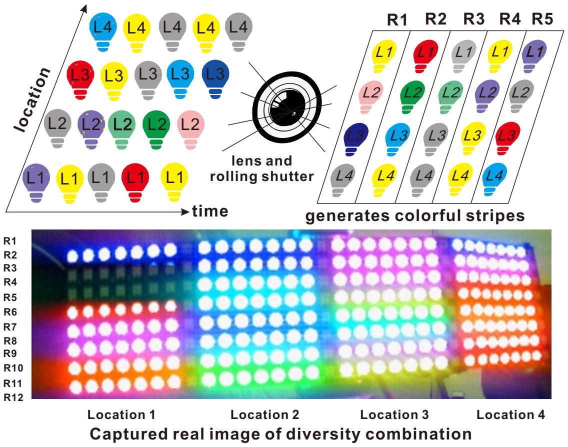

Fig. 5: Diversity combination illustration: the light from different LED elements is projected on the different pixels on the camera's image sensor via the lens.

For instance, if we adopt 4 levels of grayscale, the same as 4-CASK in amplitude diversity to represent data, adopt 4 different color (Hue) in spectrum diversity, the same as 4-CSK and transmit these 4 optical signals synchronously at 4 locations of the transmitter. These individual modulation and demodulation are very simple and reliable compared with high-order CASK, ColorBar. Nevertheless, this combination can output a total of $T = 4 \times \log_2(4 \times 4) = 16$ bits per symbol duration faster and more robust without the limitation of short symbol distance in each diversity.

### B. *Modulation Protocol Design*

Our proposed RainbowRow modulates optical signals with the combination of lightness, color, and location. For example, the transmitter has four locations, in each location, it can generate four colors with four lightness levels, as shown in Tab. I.

TABLE I: Symbol coding table for RainbowRow

| Color | Brightness | Location | | | |
|---|---|---|---|---|---|
| | | L1 | L2 | L3 | L4 |
| RED | 1 | 0000 | 0000 | 0000 | 0000 |
| | 2 | 0001 | 0001 | 0001 | 0001 |
| | 3 | 0010 | 0010 | 0010 | 0010 |
| | 4 | 0011 | 0011 | 0011 | 0011 |
| GREEN | 1 | 0100 | 0100 | 0100 | 0100 |
| | 2 | 0101 | 0101 | 0101 | 0101 |
| | 3 | 0110 | 0110 | 0110 | 0110 |
| | 4 | 0111 | 0111 | 0111 | 0111 |
| BLUE | 1 | 1000 | 1000 | 1000 | 1000 |
| | 2 | 1001 | 1001 | 1001 | 1001 |
| | 3 | 1010 | 1010 | 1010 | 1010 |
| | 4 | 1011 | 1011 | 1011 | 1011 |
| YELLOW | 1 | 1100 | 1100 | 1100 | 1100 |
| | 2 | 1101 | 1101 | 1101 | 1101 |
| | 3 | 1110 | 1110 | 1110 | 1110 |
| | 4 | 1111 | 1111 | 1111 | 1111 |

### C. *System Implementation*

There are **three challenges** for RainbowRow implementation: (1) At the transmitter side, color overlapping causes the wrong detection of the optical symbol. (2) The emitted optical signal may have flicker to human eyes due to some color/lightness appear in low frequency, which is harmful to users' health and lighting. (3) The varying optical environment will distort the transmitted optical signals and causes wrong symbol detection as well. We address these challenges at the transmitter and receiver sides below.

*1) A low-cost LED-based Transmitter Design:*

We use commercial LEDs as the OCC transmitter. To generate multiple colors, we adopt Tri-LEDs instead of single color LED for spectrum diversity. The transmitter should be composed of multiple Tri-LEDs for spatial diversity, which are synchronously controlled by the driver and deployed at proper positions on it, as shown in Fig.6 instead of single color LED arrays in [11].

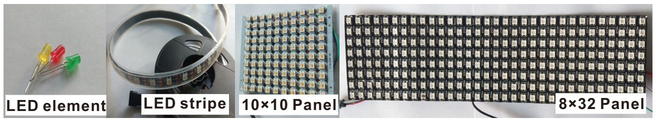

Fig. 6: LED selection. For LED stripe, 10x10 and 8x32 LED panels are based on WS2812B 5050 Tri-LED diodes.

In OCC systems, the transmitter has two functions. One is communication, and the other important function is lighting as an infrastructure. Thus, the communication process should offer constant and smooth lighting. However, even when the transmitter emits different optical signals very fast, some specific optical symbols appear in low frequency due to the probability of its presented bits. These optical signals will cause flicker, which damages the user experience for lighting, even human health. We mitigate flickers by rescheduling the coding table to increase the probability of different colors appearing in four blocks simultaneously, as shown in Fig. 7. It effectively addresses the flicker problems.

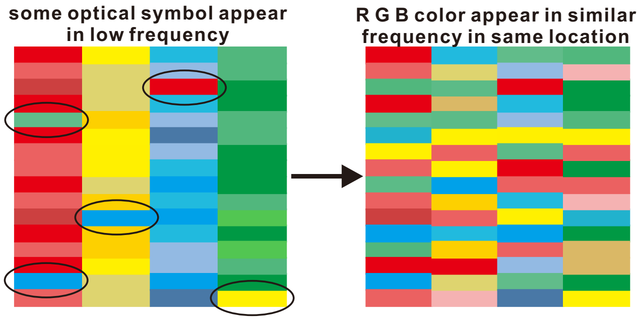

Fig. 7: Optical symbols with low appearance frequency cause flickers. We mitigate flickering by coding data with colors in the same possibilities.

However, there still faces the challenge of color overlapping. For example, when the LED block 3 emits blue color, it will have a light range not only cover the location 3, which spreads to the near blocks 2 and 4. It will mix with colors from near blocks such as the green at block 2 to generate wrong optical symbols for detection. We mitigate the overlapping influence in two ways: (1) add gap zones between near blocks, (2) select colors with far distance in the spectrum for near blocks. Although we address the color overlapping between near blocks in the row direction (horizon), there are still color mixtures between rows in the same blocks. We add row gaps to mitigate the color mixture in a vertical direction.

*2) Real-time Camera-based Receiver Design:*

At the receiver side, we convert the captured RGB to HSL values first and then use Hue and Lightness and normalize H and S value in the range of [0, 255] for spectrum and amplitude detection. Although the HSL model is better than RGB for color and amplitude detection, it still faces the color distortion and impacted by ambient light. The receiver decides the H and L threshold dynamically based on the measurement via preamble optical symbols.

As for detecting the optical signal's spatial location, we deploy/hold the camera pointing at the LED panel. We also need to select a region of interest (ROI). Different sizes and locations of ROI will influence the symbol detection accuracy. The best location of ROI should have the same horizontal center with the related blocks of LED panel. Besides, different rolling shutter frequency will generate stripes with different width as shown in Fig.8. Thus, the ROI should have the same or less height of the stripe width.

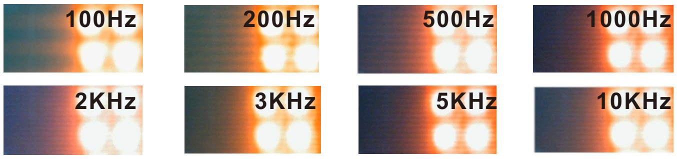

Fig. 8: Stripes generated in different frequency

**Algorithm 1:** RainbowRow Demodulation Algorithm

```
Input: O; // Optical RainbowRow Symbols
Output: D; // Decoded data bits
1 Initial Hue and Lightness thresholds H1-H3 and B1-B3
    based on the measurement of Preambles;
2 Initial ROI size and location based on captured stripes;
3 $\lambda \leftarrow 0$; // Allowed H or B variation of same symbol
4 while $\triangle H$ or $\triangle B < \lambda$ do
5     Detect H and B of O; // Four ROI in one Row
6     if $\triangle H$ or $\triangle B > \lambda$ then
7         Go to line 1;
8     Demodulate O into D based on Table I;
```

## IV. PERFORMANCE EVALUATION

In this section, we conduct experiments to evaluate the performance of RaibowRow. First, we introduce our testbed. Second, we adjust transmission frequency, ambient light, and distance to verify reliabilities for diversity combination. Last, we report SER reduction and throughput improvement compared with state-of-art modulation methods.

### A. *RainbowRow Testbed*

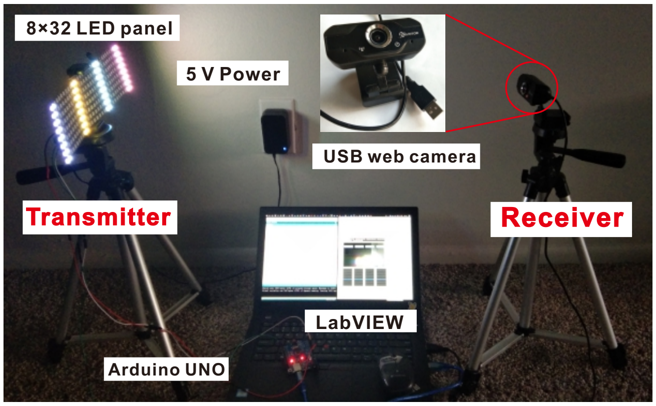

Fig. 9: RainbowRow testbed. The transmitter is a Tri-LED panel combined with Arduino UNO. The receiver is a regular web camera controlled by the LabVIEW program on PC.

The implemented RaibowRow testbed is shown in Fig. 9. We adopt an 8x32 WS2812B LED panel controlled by Arduino UNO as the transmitter and use a commercial web camera connected with PC LabVIEW as the receiver. The system block diagram is shown in Fig.10. The bits will be split into 16-bit bit sequences, and then these bit sequences will be mapped into different combination optical symbols based on the RainbowRow symbol coding table Tab. I. LED and Arduino based transmitter then generate optical signals with three diversities. The receiver then captures images via a camera and demodulate symbols into bits. Finally, the bit sequences will reconnect into the bitstream.

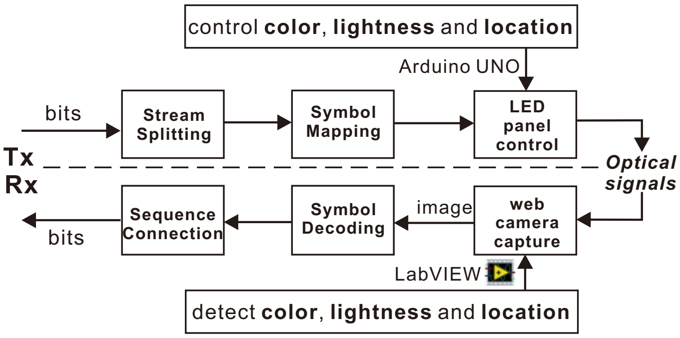

Fig. 10: RainbowRow system block diagram.

### B. *Diversity Reliablity*

RainbowRow modulation can ideally achieve a faster transmission rate through the combination of optical signal diversity, especially the utilization of spatial diversity. Nevertheless, its actual communication performance also depends on the symbol detection performance. However, in our diversity combination, spatial diversity is the most reliable due to the relatively fixed transmitter and receiver. The testbed can match locations with optical symbols correctly. As for spectrum diversity and amplitude diversity, they are more related to the optical environment. We evaluate the reliability of these two diversities by adjusting transmission frequency, ambient light strength (via adjusting the brightness level of an additional light source), and communication range on our testbed.

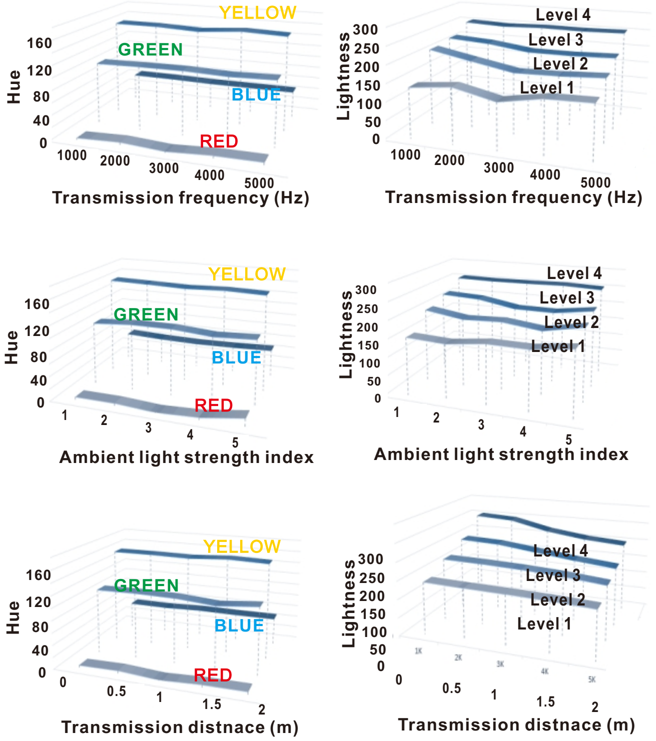

Fig. 11: Reliability of spectrum and amplitude diversities. Hue and lightness variation with increasing transmission frequency / ambient light strength / transmission distance.

1) *Hue variation:*

As shown in Fig.11, the hue value of the same color keeps constant when the transmission frequency increased from 1 kHz to 5 kHz. Moreover, among different colors, there are significant hue gaps, even the green and blue, which are in the near location on the optical spectrum. Then we keep transmission frequency at 3 kHz and distance at 1m and only change the ambient light strength. The hue variation keeps flat as well for the same color. When we only change the transmission distance, the same conclusion draws. Thus, spectrum diversity in RainbowRow is reliable for modulation in varying optical environments and different transmission requirements.

2) *Lightness variation:*

Different from spectrum diversity, the amplitude is more influenced by the environment. Firstly, when transmission frequency increases, four levels of lightness optical symbols have different variations. The brightest optical symbol keeps constant while other optical symbols go up and down with the transmission frequency, as shown in Fig.11. Then we keep the transmission frequency at 3 kHz and 1 m and only change the ambient light strength. The same thing happens, but the difference is that the gaps between different brightness level

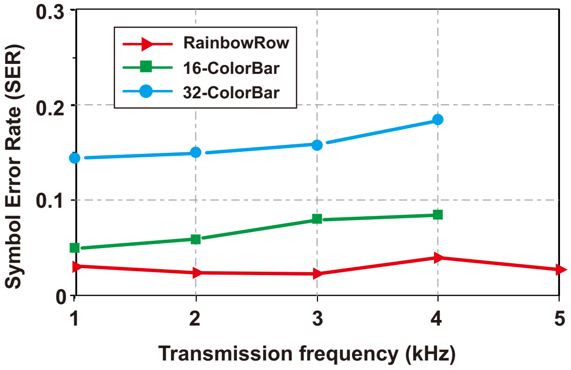

Fig. 12: SER significant reduction compared with state-of-art high-order modulation ColorBar [7].

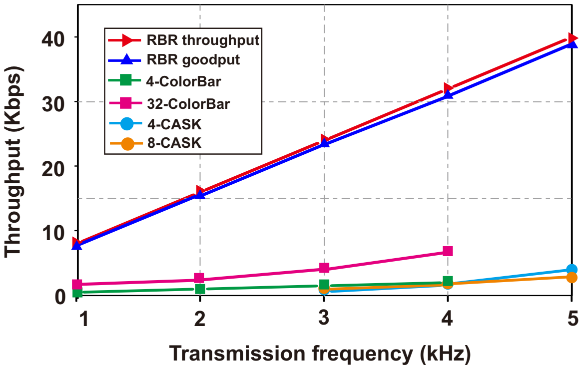

Fig. 13: Throughput improvement compared with state-of-art high-order modulation methods: ColorBar [7] and CASK [5].

symbols decrease with the ambient light strength. It will cause the symbol distance shorter even we only have four levels in the range of [0,255]. Last, we only change transmission distance. Similarly, the gaps between four levels decrease, but the obtained lightness is gathered in a low range. These results show that amplitude diversity is not as reliable as spectrum diversity. Nevertheless, due to we only have four levels in each diversity, amplitude diversity is still robust.

### C. *SER Reduction*

Compared with existing modulation methods, we adopt fewer kinds of levels and keep the considerable symbol distance in each diversity. The combination of these proper symbol distance modulation assists the SER reduction compared with other high-order modulation methods such as 16-ColorBar and 32-ColorBar, which has less symbol distance in single diversity. Besides, due to the reliability of spectrum and spatial diversity, it also improves the reliability of weaker amplitude diversity for keeping proper symbol distance. We set the ambient light strength level at 3 and transmission distance as 1 m and adjust the transmission frequency. As shown in Fig.12, compared with the 16-ColorBar and 32-ColorBar, RainbowRow achieves lower SER in different transmission frequencies. When the transmission frequency is 3 kHz, the SER of RainbowRow is less than 0.025.

### D. *Throughput Improvement*

Adopting fewer levels in each diversity is helpful for low SER compared with high order modulations. However, it may be harmful to throughput improvement. Inversely, RainbowRow transmits more than same-order modulations due to its diversity combination. We also set an ambient light strength level at 3 and transmission distance as 1 m and adjust the transmission frequency. As shown in Fig.13, the throughput of RainbowRow is higher than 4-ColorBar and 4-CASK even the high-order 32-ColorBar and 8-CASK among all the frequency. The throughput of RainbowRow is about 8 times of 4-ColorBar and 4-CASK, which use the same levels in each diversity. When the frequency is 5 kHz, the RainbowRow can achieve up to 40 Kbps.

## V. CONCLUSION

In this paper, we propose a practical and robust OCC system *RainbowRow* to boost the data rate for high-speed applications. We start from the primary color detection principle of commercial cameras and diversity features of optical signals. We propose a novel spatial related multiplexing protocol and combine it with amplitude and spectrum diversities for improved data rate. Furthermore, we address the flicker and color overlapping challenges at the transmitter and develop a robust decoding algorithm for the commercial camera-based receiver. The extensive experiments indicated that our *RainbowRow* achieves the SER less than 0.05 and the throughput up to 40 Kbps at 1 m communication range.

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