MIMO Architecture for Optical Camera Communications

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ABSTRACT

Compare with other communication system based RF technology, Optical Camera Communication (OCC) has limitation on data rate due to the low frame rate of camera. The limitation on data rate can be solved with multiple-input and multiple-output (MIMO) technology; and it is the final target of all researches on OCC. The MIMO topology can be implemented easily without breaking out the architecture of image sensor. For image sensor classification, there are two architectures have been developed: rolling shutter and global shutter. The operation of two techniques is different so the performance is also different. In this paper we analyze and evaluate the performance of the MIMO architecture for OCC.

Key Words : Camera communication, Optical camera communication, OCC, OWC, MIMO

Ⅰ. Introduction

In visible light communication technology, the receiver can be photodiode or image sensor. The light signal is converted into electric signal directly or from image quantization. Traditionally with photodiode technology, the received signal is continuous signal. However with Optical camera communication the receiving signal is discrete from captured image. The transmitting signal is represented by one group pixels at receiver. In this way, OCC can be considered as an extension of visible light communication. OCC has advantage of no extended hardware cost. The main cost of OCC receiver is the build-in camera controlling software and image processing algorithm. The OCC transmitters are single lighting sources such as LED or array light source such as LED array, display or digital signage. The architecture of OCC for a general concept can be shown in Figure 1. Compare with VLC, OCC can achieve higher directional channel.

For revision of IEEE visible light communication (VLC) specification[1], high speed photodiode and OCC are two considered approaches. One of the most consideration limitations of OCC technology is data rate. This comes from the low frame rate of commercial camera. Most of commercial camera can

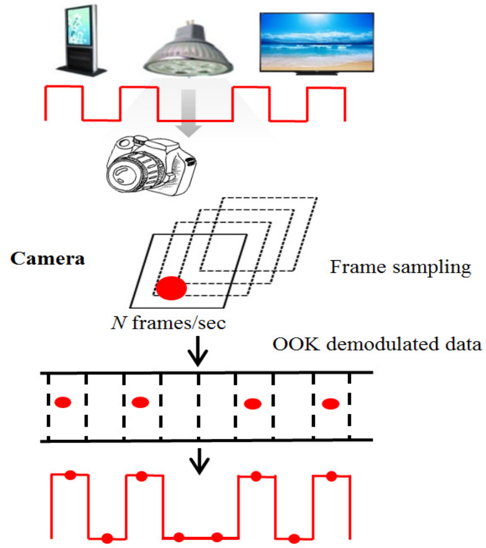

Fig. 1. Optical camera communication architecture.

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support 30 or 60 frame per second. At this rate, the OCC data rate can achieve up to tens of bits per second. Compare with other technologies, this is a big challenge of OCC. The promising solution to overcome the limitation bit rate due to the low sample rate is MIMO spatial multiplexing. Using spatially separated pixel on received image, the MIMO technique can enhance the capacity of the image sensor based visible light communication. The architecture of MIMO OCC is presented by Figure 2. The OCC MIMO concept is based on multiple transmitted elements of a light emitting array and cell demodulation in camera received image. Every cell will modulate for one bit stream. The pixels in a camera can essentially be viewed as an array of highly directional received elements.

The image sensor technology is classified by two categories: global shutter and rolling shutter. The structure and operation of two technologies are different so the perform on OCC is also different. In this paper we will analyze the performance of MIMO OCC based on global shutter and rolling shutter image sensor. The paper is organized as follows. The overview and related works of OCC will be presented in section 2. The analysis of effect and performance of MIMO OCC is presented in section 3. Finally the conclusions of the research results and contributions are in Section 4.

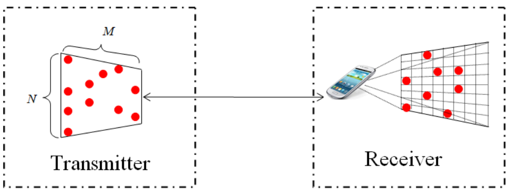


Fig. 2. MIMO OCC architecture.

Ⅱ. Related Works

For the general view, visible light communication can be classified by photon signal from photodiode or image sensor. As this classification, there are two major receiver optical choices in VLC: (i) non-imaging optics and (ii) imaging optics. Non-imaging optics is typically used with single photodiode detectors to enhance the FOV angle. In contrast, imaging optics is common and is used in conjunction with the camera image sensor. However with the business trend of image sensor, visible light communication based image sensor will move to image based communication. This is the motivation of OCC for IEEE 802.15.7 revision candidate.

The applications of OCC are distributed from indoor to outdoor topology[2]. It can be data communication such as URL link broadcasting for advertisement service[3] to ITS service such as road-to-vehicle system with hierarchical transmission scheme[4] using LED and the high-speed camera. The main difference is receiver process. The camera will generate discrete status of transmitter's light in image. The demodulation process must base on color information of image pixel. If considering the illumination function, OCC system can be classified by two modulation directions: OOK modulation and subcarrier modulation. In subcarrier modulation, the digital data is broadcasted by different frequency of on-off lighting source. Camera will detect the carrier frequency from image of light and demodulate the original data. With OOK modulation, the modulated light signal represents the digital bit by on-off state. So it cannot support the flickering avoidance.

Similarly with visible light communication, the applications and service of camera are combination of lighting purpose and communication function. There are many researches on OCC during these days. Most of the works focused on modulation, synchronization, application, or system architecture. As an extension of visible light communication, optical camera communication is considered as one issue for IEEE 802.15.7r1. Starting from 2014, the revision issues have been considered with high speed photodiode and image sensor receiver architecture. For image sensor, the contributions covered PHY modulation, MAC frame structure, and channel access algorithm. For MIMO OCC, the research is mainly focused on low rate screen modulation of high speed camera. The works are considered as global shutter image sensor[4,3]. Most researches are mainly focus on the performance analysis and synchronization issue. This paper will mainly focus on the analysis of MIMO OCC based on image sensor architecture.

Ⅲ. MIMO Architecture for OCC

3.1 Image sensor classification

Different with MIMO concept in RF system, the MIMO technique for OCC is based on imaging processing. Transmitter includes multi independent optical sources. By using image processing technique, receiver can separate the transmitter sources and recover bit data. The image sensor technology of camera receiver is classified by two main technologies CCD and CMOS which can support global shutter and rolling shutter. The image construction process of global shutter and rolling shutter is shown by Figure 3. With rolling shutter camera, the captured image is generated row by row of pixels. It means different lines of the array image are exposed at different times to read the light intensive through the sensor. Due to the time exposure delay row by row, if object is large enough and fast changing enough, the relative structure of object will record time by time. This is the cause of motion blur in captured image. However, this mechanism is the advantage in OCC. Serial of light source states will be captured in one image. For global shutter, each pixel in the sensor array begins and ends the exposure simultaneously. So, all pixels of image will get information from sensor at the same time and over the same duration. This mechanism can provide exposure capability for moving object capturing. For multimedia service it is good technique of image quality. For OCC, this mechanism can get only one state of light source in one image.

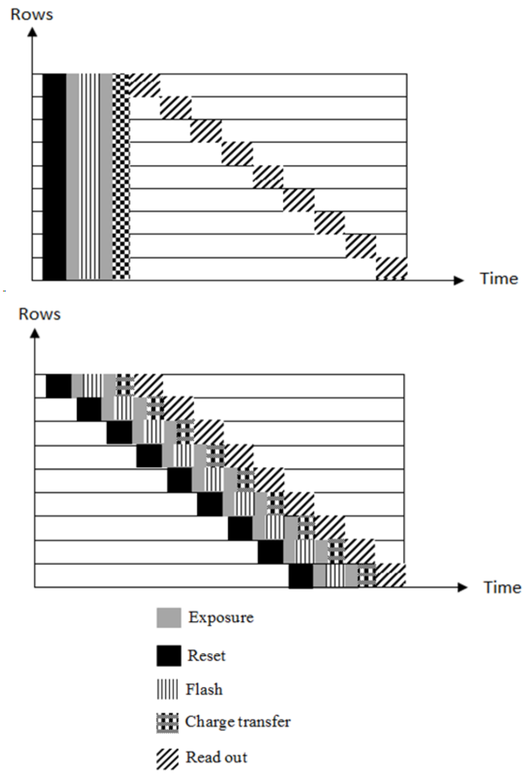
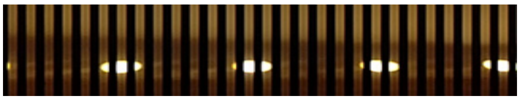


Fig. 3. Global shutter and Rolling shutter image sensor operation.

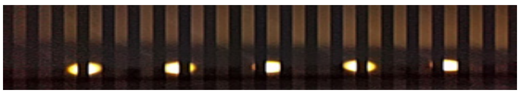
3.2 OCC Performance

One of the main advantages of rolling shutter image sensor in OCC compare with global shutter is data rate performance. One sampling image can include a serial of light transmission. As Figure 4, at different frequency of OOK the numbers of dark and grey pixel rows are different. At higher frequency of OOK, OCC can achieve higher data rate. However, the width of every roll is narrower. It will be more complex for signal decoding.

To maximize the decoded bits in one image frame, there is a restriction on the distance from image sensor and light source. If transmitter light



(a) OOK modulation at 2 kHz



(b) OOK modulation at 1.5 kHz

(c) OOK modulation at 1 kHz

Fig. 4. Image frame of different frequency OOK.

source cannot cover in the image sensor, some signal states will be missed at final image. As Figure 5, the bottom rolls include no data information, even though, the LED is in transmitting mode.

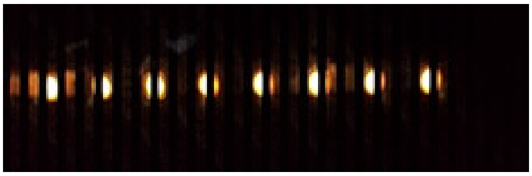


Fig. 5. Image frame of transmitter out-distance.

3.3 MIMO Architecture for OCC

As Figure 6, for maximizing the data rate of OCC system, the required distance from the LED to the camera is determined by the LED horizontal size and focus lens. The required distance from the LED to the camera is given by equation 1.

$$\text{Distance} = \frac{Light\_source\_horizontal\_size/2}{\tan(\text{FOV}/2)} \quad (1)$$

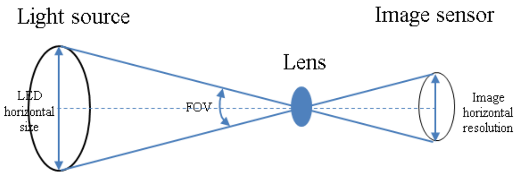


Fig. 6. Distance affection in MIMO OCC.

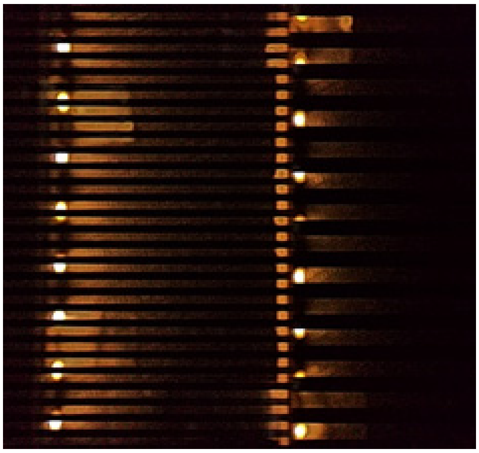


Fig. 7. F1=1kHz, F2= 1.5kHz, d=6cm FOV=90 on rolling shutter image sensor.

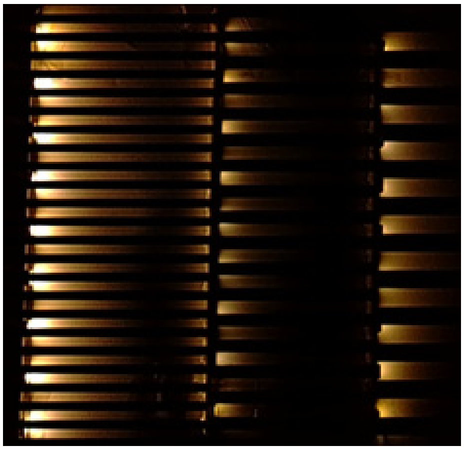


Fig. 8. F1=1kHz, F2= 1.5kHz, F3=2kHz, d=5cm, FOV=90 on rolling shutter image sensor

Figure 7 and Figure 8 show the image of 2 and 3 MIMO frequencies OOK at different separation interval with rolling shutter camera. The interference from neighbor light source is one important factor of MIMO receiver. The separation distance between transmitters depends on transmission power and LED's FOV. The optimization of number transmitter sources should be considered at different environment, hardware configuration and link distance. With global shutter image sensor, one image can record one status of light transmitters. Figure 9 and Figure 10 show the image of 2 and 3 MIMO with global shutter image sensor. From the captured image, the encoded data can be recovered one by one using computer vision.

Based on the image sensor operation and analysis, the architecture of MIMO for OCC is shown Figure 11 and Figure 12. With rolling shutter image sensor, the transmitters must align horizontally as Figure 11.

Fig. 9. 2 MIMO OCC on global shutter image sensor.

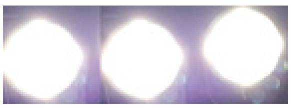


Fig. 10. 3 MIMO OCC on global shutter image sensor.

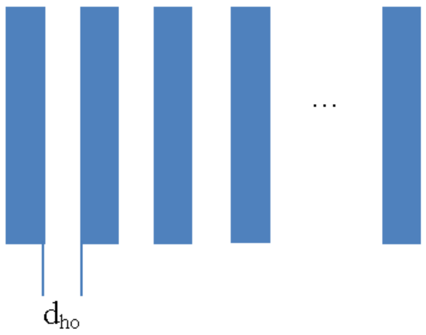


Fig. 11. MIMO OCC architecture based rolling shutter image sensor.

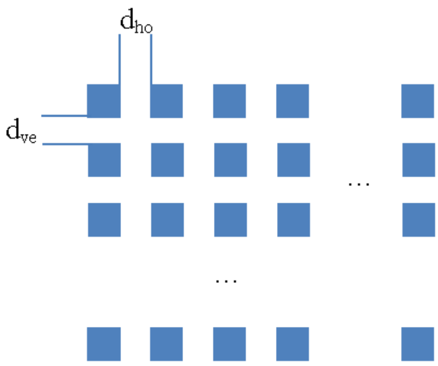


Fig. 12. MIMO OCC architecture based global shutter image sensor.

The communication range depends on horizontal size of lighting devices. With global shutter image sensor, the transmitter light sources can design as Figure 12. The communication range depends on the transmitter size and the interference from Blur Gaussian effect[5]. The interference factor is similar with rolling shutter image sensor. Compare with rolling shutter image sensor, transmitter hardware of global shutter is more complex. The data rate performance of global shutter image sensor OCC is fixed with the configuration frame rate. With rolling shutter image sensor OCC the data rate is controlled by transmitter modulation. For OOK modulation the data rate can be enhanced with higher modulation frequency. For example the number of rolling state of light source in Figure 4 follows by modulation frequency. For both rolling shutter and global shutter image sensor, the separation interval between two lighting source depend on blur Gaussian environment. For global shutter image sensor OCC, the communication range can reach until the resolvability limitation of lighting source at receiving image. With rolling shutter case the distance is controlled by horizontal size and blur Gaussian factor.

For the performance of data rate on rolling shutter and global shutter image MIMO OCC, the results are shown by Figure 13 and Figure 14. In this experimentation, we configure OCC system with OOK modulation at 1 kHz, 1.5 kHz and 2 kHz optical clock rate. The camera frame rate is at 25 fps. With rolling shutter, it can achieve higher data rate at higher frequency modulation. It is from the advantage of captured rolling. At higher frequency modulation the number roll light states will higher. Reversely, the data rate performance of global shutter image sensor depends on the camera frame rate.

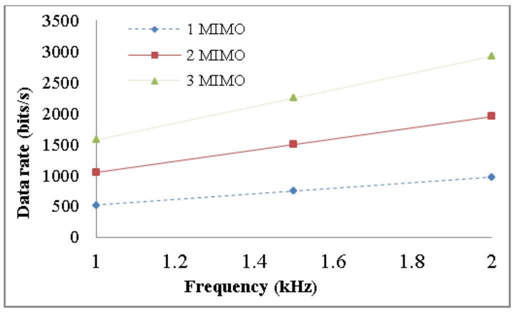


Fig. 13. MIMO OCC performance based rolling shutter image sensor.

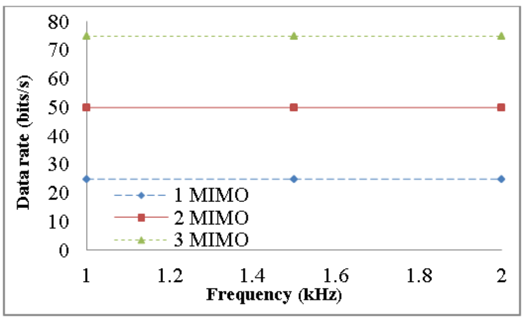


Fig. 14. MIMO OCC performance based global shutter image sensor.

Ⅳ. Conclusion

Even though the advantages on hardware architecture and communication channel, data rate is one of the most considerations of OCC. For that limitation, MIMO will be an important solution for OCC commercialization. By analysis and experimentation, this paper gave a reference model for MIMO OCC based on image sensor architecture. The performance of MIMO based on rolling shutter image sensor is better than global shutter image sensor on data rate. However for communication range, global shutter image sensor has higher advantage.

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