Optics Communications 431 (2019) 19–28

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Wide receiver orientation using diffuse reflection in camera-based indoor visible light communication

Willy Anugrah Cahyadi, Yeon Ho Chung *

Department of Information and Comm. Eng., Pukyong National University, Republic of Korea

ARTICLE INFO

Keywords:
Indoor communication
Optical imaging
Optical receivers
Optical transmitters
Visible light communication

ABSTRACT

Camera-based visible light communication (CVLC) is a versatile and potential optical wireless communication using rapidly developing smartphone cameras as the receiver. In CVLC, the provision of both flicker-free illumination and high data rate has been a challenging issue. To some extent, however, this issue can be resolved by utilizing a rolling shutter property that is inherited from complementary metal-oxide semiconductor sensors adopted in all smartphone cameras. We propose a practical and versatile wide receiver orientation in CVLC on the basis of this rolling shutter property. That is, unlike previous studies focused on either a line-of-sight (LOS) or non-line-of-sight (NLOS) link only, an orientation independent rolling shutter based CVLC is presented. Based on a unique method of exploiting diffuse reflection of illumination, a wide orientation of the receiver is adequately supported in an indoor environment, thus making the CVLC data reception more practical and convenient. A special transmitter for this wide orientation is designed to ensure that adequate diffuse reflection is present in all directions, regardless of whether a LOS or NLOS link is established. In addition, adaptive algorithms are proposed to ensure an efficient and reliable wide orientation CVLC. Experiments are conducted and analyzed for practical orientations of the receiver in an indoor CVLC environment. While providing sufficient illumination and various orientations, it is found that the proposed scheme achieves a data rate of 6.72 kbps at a distance of up to 50 cm in a small-scale indoor experiment.

1. Introduction

The rapid development of a smartphone camera and its cost reduction have recently motivated a camera-based visible light communication (CVLC) that uses a camera as the receiver [1–5]. CVLC is defined as a part of visible light communication (VLC) scheme employing visible light as a communication medium and uses an image sensor as its receiver that has an advantage of 2-D image acquisition, compared with 1-D data acquisition on a photodiode based VLC [1,4,5]. While VLC provides illumination and high speed indoor communication, CVLC is considered both versatile and promising for future wireless communications as an extension of IEEE 802.15.7 standard [1,5,6].

It is due to the 2-D image acquisition having millions of pixel data that CVLC has a drawback of very slow capture rate, compared with VLC. A slow capture rate of the camera, which is generally confined to 120 fps or lower for mobile devices, hampers the illumination provision in CVLC and limits its data rate. The transmitting LEDs in CVLC cannot be flickered faster than the capture rate of the camera, i.e., flickered lower than 120 Hz, thus making it inapplicable for lighting purposes [2,5]. Moreover, CVLC transmitters generally use LED arrays with multiple colors that make it inappropriate for indoor illumination [1,7]. In this regard, a CVLC scheme with additional LEDs dedicated for illumination was proposed [1]. To ameliorate the limited capture rate of CVLC, some authors utilized a rolling shutter effect (RSE) of complementary metal-oxide semiconductor (CMOS) sensor [2–5]. The RSE based CVLC reads each pixel row sequentially in each captured frame, thus increasing an efficient capture rate of the camera, depending largely on the vertical resolution of the camera (number of pixel rows) [2–5,7]. A net data rate of 5.76 kbps was recently reported on RSE based CVLCs, which is a significant increase compared with a CVLC conventional data rate of 150 bps [8]. However, all RSE based CVLCs are focused on either only line-of-sight (LOS) or only non-line-sight (NLOS) communication link with specific orientations of the receiver [2,3,7,9]. It is obvious that practical CVLCs must be designed to support wide orientations of the receiver (camera) in a CVLC. To be more specific, supposing that the user is on the move in an indoor environment, the transmitter needs to be designed to support a LOS or NLOS link, regardless of the receiver orientations.

We propose a wide receiver orientation (WRO) functionality in CVLC utilizing a diffuse reflection with the provision of the illumination and high data rate. The proposed scheme employs the specially designed transmitter and a set of adaptive algorithms in the receiver, in order to utilize the diffuse reflection of the illumination light. The main idea of

* Corresponding author.
E-mail address: yhchung@pknu.ac.kr (Y.H. Chung).

https://doi.org/10.1016/j.optcom.2018.09.009
Received 6 August 2018; Received in revised form 4 September 2018; Accepted 5 September 2018
Available online xxxx

the proposed scheme is that the diffuse reflection is widely distributed through surrounding walls and ceiling in an indoor environment, which makes it largely accessible for the receiver in multiple orientations. In this regard, the proposed scheme supports both a LOS and NLOS link. The method of capturing the diffuse reflection in the proposed scheme can be viewed as indirect capturing from the LEDs. It is found that the proposed scheme provides a high illumination level of 152 lx and thus ensures adequate communication quality up to a distance of 50 cm. In addition, a set of adaptive algorithms for the proposed scheme is developed for maintaining communication quality. The proposed scheme is evaluated employing several materials of the wall for the diffuse reflection as well as multiple receiver orientations in a lab-scale experiment.

The rest of the paper is organized as follows. In Section 2, we describe the overview of diffuse reflection based CVLC, followed by the proposed WRO in CVLC in Section 3, and the experiment results and analysis are described in Section 4. Conclusions are drawn in Section 5.

2. Diffuse reflection based CVLC

2.1. Principle

The proposed scheme is illustrated in Fig. 1(a). It exhibits the specially designed transmitter and the smartphone camera as the receiver. The proposed transmitter is connected to a microcontroller unit (MCU) that is installed outside the experiment chamber. The proposed scheme supports multiple orientations through the diffuse reflection of the illumination light emitted from the transmitter, as opposed to the previous studies confined to either LOS or NLOS orientation [2–4]. The indoor coverage of the proposed scheme is ensured by an equal distribution of illumination throughout the chamber room that provides adequate diffuse reflection in any orientation. It is important to note that the advantage of utilizing the diffuse reflection is that the receiver does not need to capture the transmitter directly in a straight line as long as the diffuse reflection can be captured. Thus, a dynamic movement of the receiver is supported for the proposed scheme during the transmission, which makes it very practical because the smartphone can conveniently be hand-held or in a slight motion rather than on strict static hold as investigated in the previous study [2]. Multiple orientations are illustrated in Fig. 1(b). Unlike previous studies [2–5,7], various orientations, i.e., θ value ranging from 0° to 90°, are employed in the proposed scheme and subsequently analyzed through the experiments.

Fig. 1(c) shows the experimental block diagram for the proposed scheme. The data packet is generated in a personal computer and sent to the MCU. The MCU then loads the data packet and the data packet is modulated with on–off keying (OOK). The modulated data is finally transmitted through the transmitter LEDs. On the other hand, the smartphone camera acting as the receiver captures the diffuse reflection from the transmitter. The captured video from the smartphone camera is passed on to a personal computer for offline demodulation and data packet retrieval. Fig. 1(d) shows a real experimental setup of the proposed scheme in an indoor chamber, including an enlarged photo of the proposed transmitter during operation. The surface of the chamber wall for evaluating the scheme is varied among three different materials having different reflectance properties, i.e., white wood panel, white paper, and glossy polyvinyl chloride (PVC) wallpaper. These materials are selected to represent typical indoor walls. The detailed experiment and analysis in multiple orientations are described in Section 3.

In order to ensure an equal distribution of diffused reflection from the transmitter, the design and arrangement of the LEDs are carefully performed. A hemispherical shape is employed for the transmitter design, comprising one central LED, four directional LEDs, and a diffuser as the outermost cover as depicted in Fig. 2. The central LED is placed for illumination, whereas the directional LEDs are designed for both expanding the illumination distribution and enabling efficient communication. The LEDs are installed and fixed at their positions using a polymorph plastic that also functions as the diffuser and cover in a hemispherical shape. The diffuser is employed to blend the light emission equally for all LEDs. Both the bottom view and the side view of the transmitter are presented in Fig. 2(a) and (b), respectively. The diameter of the current transmitter is 7 cm and the directional LEDs are positioned facing four sides with a 90° angle between adjacent LEDs. Observed from the side view, the thickness of the proposed transmitter is 2.5 cm and an outward tilt of 30° is set between the axis of directional LEDs and the axis that is perpendicular to the ceiling surface (the surface normal).

It is worth noting that the proposed scheme requires robust adaptive algorithms to ensure adequate communication from both LOS and NLOS links and to compensate the dynamic movement of the receiver over any orientation.

2.2. Channel model

The formulation for CVLC channels has not been addressed completely in both LOS and NLOS links [2–5]. The proposed WRO in CVLC employs an experiment for both LOS and NLOS links based on an investigated and approximated channel model in an earlier study [10]. The illuminance value measured in the proposed scheme defines the total luminous flux incident on a surface of a camera sensor that directly affects the communication quality of CVLC. An $\frac{E_b}{N_0}$ value of each pixel on the sensor of camera, which is directly related to the amount of illuminance received, is described in as [10]

$$\frac{E_b}{N_0} = \frac{E[s^2]}{E[n^2]} \approx \frac{a^2 t}{\alpha a t + \beta} \quad (1)$$

where E_b represents the energy per bit, N_0 represents the spectral noise density, s is the pixel value, a is the amplitude of the signal, t is the camera exposure duration as a ratio of the signal cycle, n is noise value, whereas both α and β are noise model fit parameters. Since the proposed scheme fixes the value of t to 1/6000 s and employ a camera with fixed noise model fit parameters (α and β), the value of $\frac{E_b}{N_0}$ is affected only by the amplitude (a). The amplitude is practically the received illuminance on the camera, regardless of LOS or NLOS links.

3. Proposed wide receiver orientation

In the CVLC, we capture an image and retrieve the data by performing an image processing. The RSE based CVLC schemes evaluate the intensity of the pixels mostly in grayscale by discarding color information. The intensity value of each pixel, denoted by N_p, is formulated specifically to address the intensity for the RSE based CVLC that utilizes the diffuse reflection.

$$N_p = K\left(\frac{tS}{f_s^2}\right)\left(\frac{E_\rho}{\pi}\right) \quad (2)$$

where K is a calibration constant for the camera, f_s is an aperture of the lens, t indicates the exposure time of the camera, and S is the ISO sensitivity of the camera sensor. $\frac{E\rho}{\pi}$ indicates a total amount of luminance of the diffused reflection entering the camera. That is, E is the illuminance that falls on the camera surface (sensor), while ρ is the reflectance of a surface that causes the diffuse reflection. It can be observed that using a fixed camera, the values of K and f_s are assumed constant. In the proposed scheme, a single camera with an f_s of f/1.8 is used. S is fixed to 2700 to achieve the highest sensitivity to light, whereas t is set to 1/6000 s to obtain the highest response time to capture the flickers of the LED transmitter. Therefore, the remaining variables are E (illuminance) and ρ (reflectance), which directly affect the intensity value (N_p) captured within each pixel of the camera.

The proposed WRO in CVLC captures the diffuse reflection of the transmitter, i.e., indirect capturing. It is apparent that the most significant intensity of the captured light, N_p, exists on the LOS link, due