Received January 17, 2019, accepted February 1, 2019, date of publication February 13, 2019, date of current version March 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2898423

VLC/OCC Hybrid Optical Wireless Systems for Versatile Indoor Applications

DUY THONG NGUYEN, SANGCHEOL PARK, YOONSUNG CHAE, AND YOUNGIL PARK
Department of Electronic Engineering, Kookmin University, Seoul 02707, South Korea

Corresponding author: Youngil Park (ypark@kookmin.ac.kr)

This work was supported in part by the National Research Foundation of Korea of the Ministry of Education under Grant NRF-2018R1D1A1A09083825, and in part by the National Research Foundation of Korea of the Ministry of Science, ICT and Future Planning of Korea Government under Grant NRF-2017M1A3A3A02016524.

ABSTRACT In this paper, a hybrid scheme for optical wireless communications using LED lamps is proposed. This scheme allows both visible light communication (VLC) using photodetectors and optical camera communication (OCC) using image sensors of a camera to receive light signals from the same transmitter simultaneously. High-frequency signals are received by VLC, while low-frequency signals are received by OCC. This hybrid transmission system enables the provision of versatile indoor services and allows users to receive data regardless of their device. It reduces the deployment cost of an indoor optical wireless system since the proposed system can provide both services using one LED lamp. To use the dimming property of LED lamps, a variable pulse position modulation scheme is used for OCC, while Manchester coding is used in VLC to avoid flickering. The measurement shows that the transmission distance reaches more than 4 m for both services. Performance analysis and experimental results are presented.

INDEX TERMS Visible light communications, optical camera communications, variable pulse position modulation, VLC/OCC hybrid.

I. INTRODUCTION

Light Emitting Diode (LED)-based visible light communication (VLC) has attracted much attention in recent research [1], [2]. It is expected to replace traditional radio frequency based systems due to its low cost, high data rate and negligible impact on human health. Optical camera communication (OCC) is a part of VLC, but it uses an image sensor as a receiver [3]–[13]. With the ever-increasing use of mobile devices, the OCC technology is believed to play an important role in the provision of internet of thing (IoT) and the 5G wireless network [7]. Compared to VLC that use photodetectors (PD) at the receiver, OCC has a lower data rate since it receives data using an image sensor. However, OCC is preferred in the application where mobility is important since most smartphones or smart devices have cameras and connect to internet easily. Therefore, OCC can be used in indoor navigation systems [8], [9], vehicle-to-vehicle transmissions [10]–[12] and mobile payments [13], etc. By the way, VLC is designed for high-speed internet access systems [14] supporting video streaming services and downloading large-size files. Recent researches on VLC shows data rate up to 10 Gbps by employing orthogonal frequency division multiplexing (OFDM) [15], [16]. The disadvantage of VLC, however, is that it requires additional optical devices such as PDs and lens in addition to smartphones.

Although both VLC and OCC use LED lamps as their transmitter, there has been no study to integrate them in a single module. Since these communications have the line-of-sight property, users should search for the appropriate lamp when VLC and OCC are serviced from different LEDs. If they are integrated, however, users can have the service from the same LED lamp regardless of their device or application. One of the problems in their integration is regarded as the difference in their operating frequencies. Unlike PDs, image sensors cannot recognize high-frequency signals due to its slow response time [17]. VLC has been combined with power line communication (PLC) [18], [19] to communicate with PDs. However, OCC requires another LED lamp due to its much lower frequency range. The other difficulty is that VLC and OCC interfere with each other as both of them are using the same visible light, working as noise at the other's receiver.

The associate editor coordinating the review of this manuscript and approving it for publication was Cheng Qian.

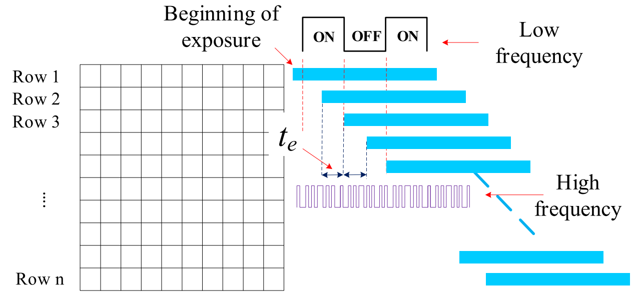

FIGURE 1. The relation between exposure time and signal frequency.

These problems are solved in this study by combining two types of line coding, i.e., Manchester coding for VLC and Variable Pulse Position Modulation (VPPM) for OCC. Based on this combination, this paper proposes a system which can transmit to PDs and cameras simultaneously, but at different data rates through the same physical transmission channel. Hence, the information of the two systems can be conveyed in parallel. We call it a hybrid VLC/OCC system in this paper.

II. SYSTEM ANALYSIS OF THE HYBRID SYSTEM

The main function of an image sensor in a smartphone is to capture an image. However, it can used as a receiver in OCC by detecting the intensity of the light signal at each pixel. The performance of OCC is much lower than that of the VLC since its structure is not designed for data transmission. This section explains the different property of signals at VLC and OCC. Then, the hybrid system is proposed by exploiting this difference. The packet structure of the hybrid scheme is designed to simplify the decoding process at the receiver. Moreover, algorithms are proposed to further improve the data rate of VLC.

A. OPERATION OF OCC

With the rolling-shutter mechanism of complementary metal-oxide-semiconductor (CMOS) image sensors, the data rate of OCC can be improved as demonstrated in [3]–[5]. Yet, the data rate of OCC is still low compared to that of the PD-based VLC, which is attributed to the fact that the operating frequency of image sensors depends on the shutter speed. The amount of received light at the image sensor is controlled by opening and closing of the shutter [20]. The image sensor receives light only for a specific period called exposure time t_e in Fig. 1, which is inversely proportional to the frame rate.

Each bit requires integer multiple of rows, n_{row}, in the image sensor as in equation (1), where T_b is a bit period and t_e is exposure time.

$$T_b = t_e \times n_{row} \quad (n_{row} = 1, 2, \ldots) \tag{1}$$

Due to the detection mechanism of OCC, the larger n_{row} guarantees the higher signal-to-noise ratio (SNR) [4]. If a bit period is smaller than an exposure time, then the camera cannot distinguish the ON/OFF states of the signal, causing inter-symbol interference. The data rate of the OCC system is also affected by the frame rate and the inter-frame gap (IFG) [4], [5].

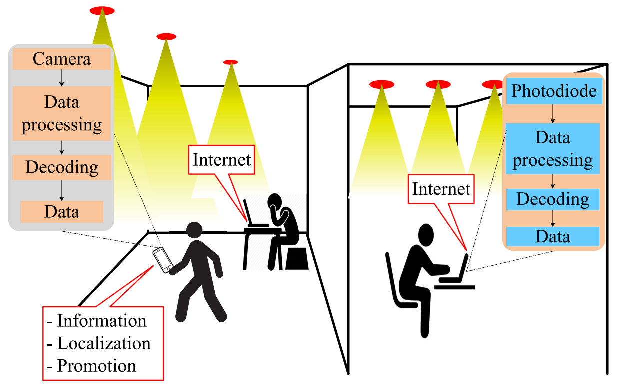

FIGURE 2. The concept of the VLC/OCC hybrid system.

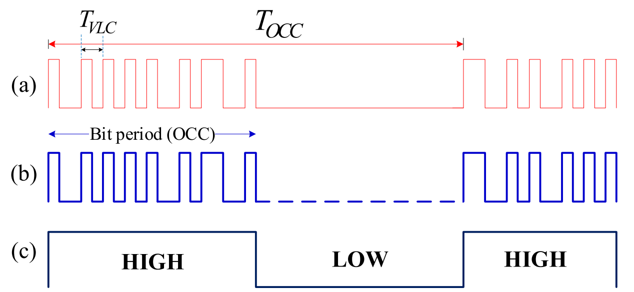

FIGURE 3. Signals in the hybrid system. (a) Transmitted signals. (b) Received signals at PDs. (c) Received signals at image sensors.

B. PROPOSED HYBRID SYSTEMS

As depicted in Fig. 2, a hybrid VLC/OCC system is the one that can communicate with both PDs and image sensors using the same LED lamp; high-speed VLC signals and low-speed OCC signals are transmitted in a combined form. Therefore, it can provide diverse services to users with reduced complexity of lighting systems at low cost since all LED lamps are equipped with the same type of modems and driving circuits, and can share the same data network. In addition, electric energy can be saved since the number of required number of lamps for communication is reduced.

In this scheme, a packet of high-frequency VLC signals is transmitted during a 'high' period of OCC as shown in Fig. 3(a). When the OCC signal level is 'low,' VLC stops sending its data. At the receiver side, it is expected that PDs recognize the high-frequency signal as shown in Fig. 3(b) while image sensors do not due to its slow response time. Although the image sensors are not able to distinguish each bit of the high-frequency signals, it recognizes the envelope of them as illustrated in Fig. 3(c). Therefore, when combined signals in Fig. 3(a) are transmitted, they are decoded into different forms as shown in Fig. 3(b) and Fig. 3(c) at PDs and image sensors, respectively.

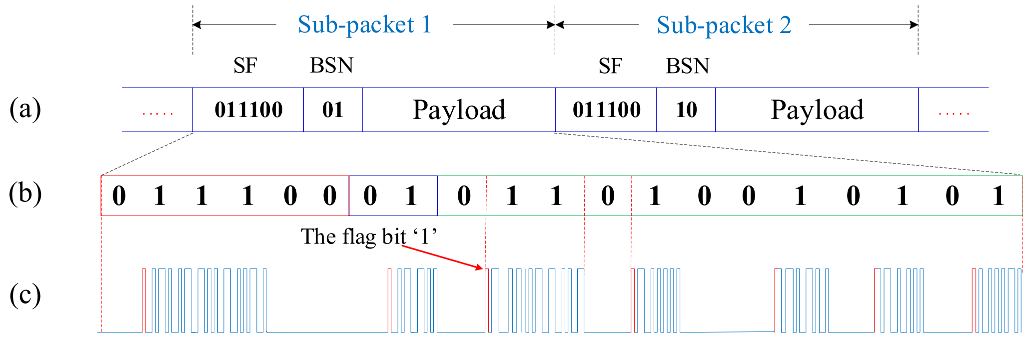

FIGURE 4. The packets of OCC and VLC in the proposed hybrid system. (a) OCC packet structure. (b) OCC data. (c) Hybrid system data.

C. PACKET STRUCTURE OF THE HYBRID VLC/OCC

In this system, Manchester coding is used in the line coding of VLC while VPPM in OCC, respectively. Manchester is used since it reduces flickering and helps easy decoding, while VPPM is used to control the brightness of the LED lamp. Brightness is controlled at the OCC side to acquire the large control range without any effect on VLC. If the dimming is controlled at the VLC side, then it changes the intensity of both VLC and OCC, leading to performance degradation at both sides.

Data packets of the OCC are transmitted in multiple times as indicated in Fig. 4 since the number of received bits in each image frame must be larger than that in a sub-packet to avoid the bit loss in the IFG. Especially, as the transmission distance increases the number of received bits per a frame reduces due to reduced power at the edge of the image sensor, causing more bit loss in the IFG [5]. It should be considered in the structure of the sub-packet as demonstrated in [4] and [5]. A sub-packet comprises a start frame bit (SF), a bit sequence number (BSN) and a payload as shown in Fig. 4(a). By the way, a sequence of VLC data is carried on the 'high' period of OCC as shown in Fig. 4(c). To indicate the start of VLC signals, a flag bit is added in the beginning of each VLC packet. The last bit of the VLC packet is recognized at the VLC receiver by counting the number of bits after the flag bit.

D. DATA RATE AND PERFORMANCE ESTIMATION

It is assumed that the data rate of VLC is an integer multiple of the data rate of OCC as in (2) at 50% brightness, meaning N bits of VLC are transmitted during an OCC bit period T_{OCC}.

$$R_{VLC} = N \cdot R_{OCC}, \tag{2}$$

where R_{VLC} and R_{OCC} are the data rate of VLC and OCC, respectively. Compared to pure VLC, the data rate of hybrid VLC at 50% brightness is reduced to half since data is transmitted only in the 'high' period of OCC. It changes with dimming of LEDs [21] as illustrated in Fig. 5. Therefore, equation (2) can be rewritten as in equation (3), where M is

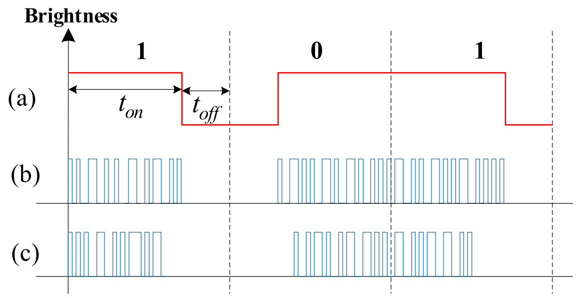

FIGURE 5. Data rate of VLC as a function of the brightness of OCC. (a) Pure OCC 70%. (b) VLC with OCC 70%. (c) VLC with OCC 60%.

the brightness (%) of OCC.

$$R_{VLC-PD} = \frac{M \cdot N}{50} R_{OCC} \tag{3}$$

Performance of the hybrid VLC/OCC system changes with the brightness of the LED lamp decided by the VPPM modulation. The bit error probability of hybrid OCC, P_b, is estimated as in equation (4).

$$P_b = 1 - \sum_{m=0}^{\lfloor r_0/2 \rfloor} \binom{r_0}{m} P_r^m (1-P_r)^{r_0-m} \cdot \sum_{k=0}^{\lfloor r_1/2 \rfloor} \binom{r_1}{k} P_r^k (1-P_r)^{r_1-k}, \tag{4}$$

where r_0 and r_1 are the number of rows for bit '0' and bit '1' in OCC, respectively, P_r is the error probability of each row of the image sensor. It is assumed that a bit error occurs when more than half rows of r_0 or r_1 are in error. The parameter $r_1 \div (r_0 + r_1)$ corresponds to the brightness, and P_b is minimum when $r_0 = r_1$, meaning 50% brightness in equation (4). Then, the performance degrades when it deviates from 50%, which is proved by experiments in the next section.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

In order to test the performance of the proposed scheme, a hybrid VLC/OCC system is implemented as shown in Fig. 6. Data of combined systems are generated and provided to the FPGA board (Xilinx Virtex-5, XC5VLX50T),

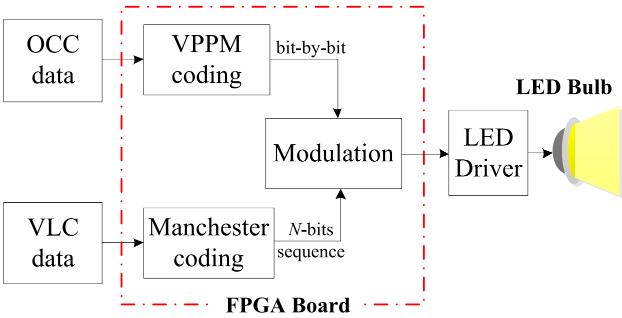

FIGURE 6. The transmitter of the hybrid VLC/OCC.

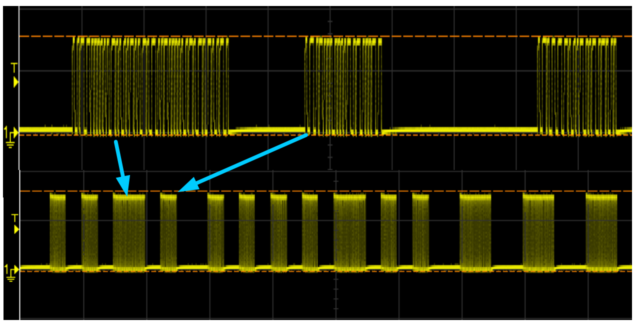

FIGURE 7. Received signals at the PD.

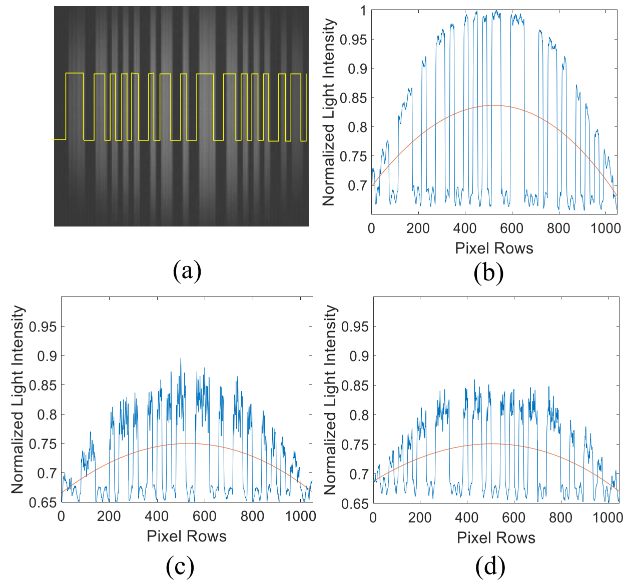

FIGURE 8. The received signals at the image sensor at 3.2 m. (a) Rolling shutter pattern. (b) Pure OCC. (c) Hybrid, R_{VLC} = 100 kbps. (d) Hybrid, R_{VLC} = 400 kbps.

and then its output is provided to the LED lamp (15 Watt) via an LED driver circuit. At the OCC receiver, a USB camera (FL3-U3-132C-CS, frame rate 60 fps, lens diameter 25 mm, resolution 1328 × 1048) is connected to a computer, where Matlab is used for the data recovery. Concerning the VLC system, a PD (S6869) and another FPGA board are used to receive and decode the signal. Data rates of the VLC and the OCC are 100 kbps and 1.67 kbps in this experiment, respectively.

Signals received at the PD are shown in Fig. 7 while signals received at the image sensor are shown in Fig. 8. It is found in Fig. 7 that high-frequency VLC signals are carried by the 'high' level of the OCC signal.

A sequence of stripes in the image frame of Fig. 8(a) comes from the rolling shutter effect of CMOS image sensors. Intensities measured at all pixels in each row are added and their normalized values are displayed in Fig. 8(b)-(d). The pure OCC signal and the VLC/OCC hybrid signal with different VLC data rates are shown in sequence. Compared to the pure OCC signals in Fig. 8(b), the amplitudes of the hybrid signals in Fig. 8(c)-(d) are reduced to half since only the 'high' parts of OCC are modulated again for VLC. The received signals fluctuate more with 100 kbps VLC modulation in Fig. 8(c) than the one with 400 kbps modulation in Fig. 8(d), which is attributed to the fact there is an incomplete part of a period of VLC signals in a row of pixel, and this part is larger with lower VLC data rate, causing more intensity fluctuation and degrading the transmission performance. It is analyzed in equations (5)-(7).

The relation between the exposure time, t_e, and the bit period of VLC, T_{VLC}, can be represented in equation (5). In this equation, t_e corresponds to the time of each row, which is larger than T_{VLC} since VLC has a very high data rate.

$$t_e = (n + r) \cdot T_{VLC}, \quad n \in, \ 0 \le r < 1 \tag{5}$$

Then, the fluctuation of OCC in the presence of VLC found in Fig. 8 (c)-(d) can be calculated as in (6).

$$I_{\max} = I_H(t)\frac{(0.5n + r)T_{VLC}}{(n + r)T_{VLC}},$$
$$I_{\min} = PI_H(t)\frac{0.5n \cdot T_{VLC}}{(n + r)T_{VLC}} \tag{6}$$
$$\Delta I = I_H(t)\,\frac{r}{n + r}, \tag{7}$$

where $I_H(t)$ is the light intensity received at each row of pixels without any modulation and $0.5n$ is used to reflect the Manchester coding of VLC modulation. Therefore, the maximum fluctuation in the OCC signals can be defined as in (7), which will become smaller with larger n, meaning high data rate of OCC. This fluctuation noise is added to other noise sources such as ambient light, the input offset voltage of LED and varying exposure time. Fig. 9 shows the BER of OCC in the proposed hybrid system with different brightness levels. The experiment results indicate that a BER value of 10^{-4} is achieved at a distance of 5.8 meters with 50% brightness, but this distance is reduced to 5 meters with 80% brightness, which is expected in (4). As the receiver moves closer to the LED lamp, the BER measurement shows error-free transmission at all the brightness. The influence of the VLC modulation on the OCC of the hybrid system is shown in Fig. 10, where the performance of pure OCC is compared with that of hybrid OCC. It is found that the transmission distance of hybrid OCC is around 6 meters at the

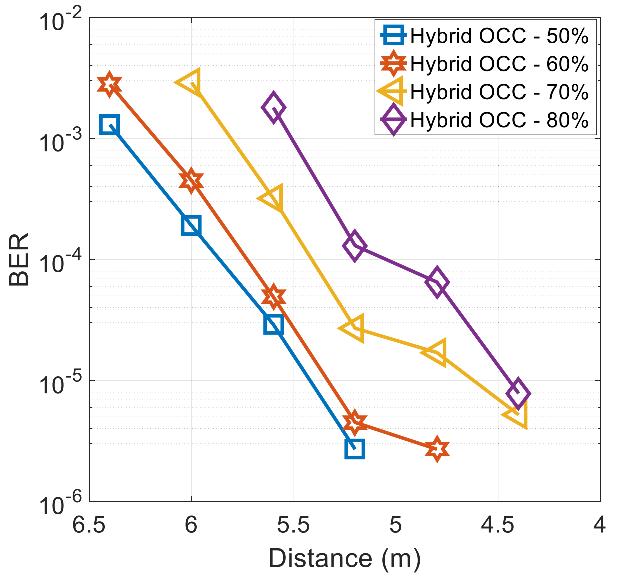

FIGURE 9. Performance of OCC in the hybrid system for different brightness.

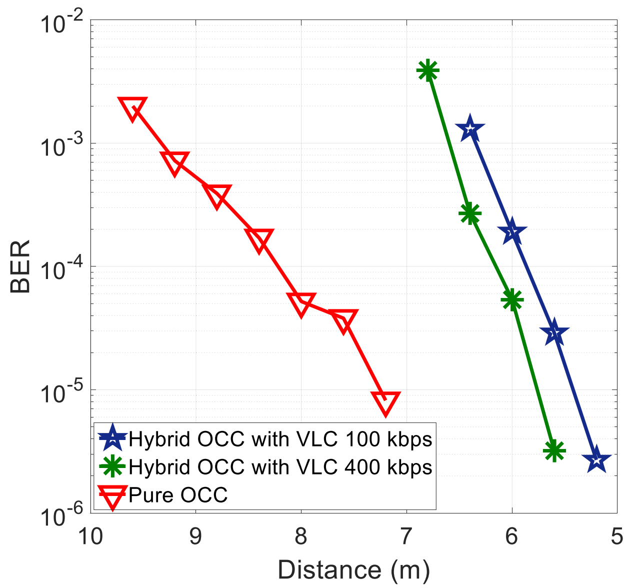

FIGURE 10. Performance of OCC in the hybrid VLC/OCC for different VLC rates.

BER of 10^{-4}, while that of pure OCC is more than 8 meters. It occurs from the reduced power of the hybrid system as illustrated in Fig. 8. By the way, hybrid OCC with 100 kbps VLC has 0.3 dB more power penalty compared to that with 400 kbps VLC, which is attributed to the larger fluctuation at lower data rate as shown in Fig. 8(c)-(d). The performance of VLC in hybrid VLC/OCC in different brightness is measured as shown in Fig. 11, where brightness is controlled by the VPPM of OCC. Unlike OCC shown in Fig. 9, the BER of hybrid VLC increases with higher brightness; as it reaches 80% the BER becomes close to that of pure VLC. After the separation of the VLC signals from the hybrid ones, level recovery of the VLC signals is essential for the data decision

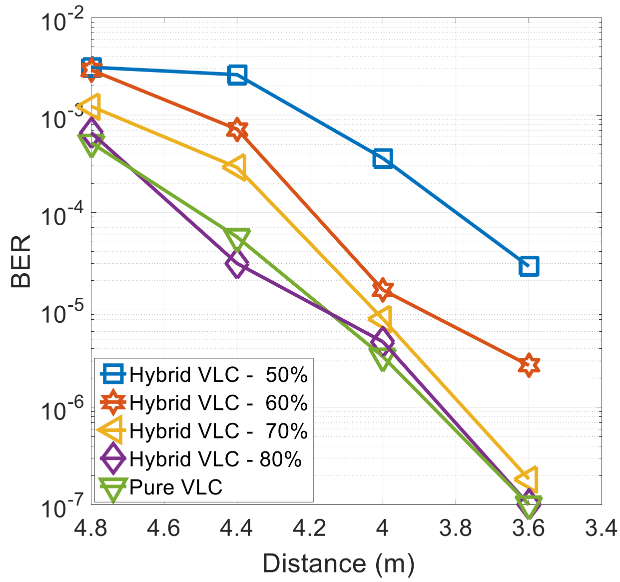

FIGURE 11. Performance of VLC in the hybrid system for different brightness.

of each bit. However, this level recovery becomes harder with lower brightness since the average of the hybrid signals falls below the average of the VLC signal as can be expected from Fig. 5, which causes more errors in the decision process. It is expected that this error is lessened with a fast level recovery scheme.

IV. CONCLUSIONS

In this paper, we propose a hybrid VLC/OCC system that enables diverse applications at less complexity and low cost. In this system, VPPM modulation is employed in OCC modulation for the purpose of dimming, while Manchester modulation is used in VLC that utilizes only the ‘high’ part of the OCC signals. It is found from the experiment that the brightness affects the performance of VLC and OCC in different way; the higher, the better for VLC, while the opposite is true for OCC. The data rate of VLC affects the OCC performance; VLC signals with lower rate degrades the OCC more since it causes more fluctuation in the OCC signal. Since VLC and OCC affect with each other, the hybrid VLC/OCC should be designed considering these impairments. A bit error rate of 10^{-4} is achieved for both OCC and VLC, at 5.8 meters and 4 meters, respectively. It is expected that the proposed system will provide various new indoor services to users whether they own smartphones or specific VLC receivers equipped with a photodiode.

REFERENCES

[1] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Ligh*, IEEE Standard 802.15.7, Dec. 2018. [Online]. Available: http://standards.ieee.org/findstds/standard/802.15.7-2011.html

[2] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, “Visible light communication, networking, and sensing: A survey, potential and challenges,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 4th Quart., 2015.

[3] C. Danakis, M. Afgani, G. Povey, I. Underwood, and H. Haas, "Using a CMOS camera sensor for visible light communication," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 1244–1248.
[4] D. T. Nguyen and Y. I. Park, "Data rate enhancement of optical camera communications by compensating inter-frame gaps," *Opt. Commun.*, vol. 394, pp. 56–61, Jul. 2017.
[5] D. T. Nguyen, Y. Chae, and Y. Park, "Enhancement of data rate and packet size in image sensor communications by employing constant power 4-PAM," *IEEE Access*, vol. 9, pp. 8000–8010, Feb. 2018.
[6] Z. Zhang, T. Zhang, J. Zhou, Y. Lu, and Y. Qiao, "Thresholding scheme based on boundary pixels of stripes for visible light communication with mobile-phone camera," *IEEE Access*, vol. 6, pp. 53053–53061, 2018.
[7] T. Nguyen, A. Islam, M. T. Hossan, and Y. M. Jang, "Current status and performance analysis of optical camera communication technologies for 5G networks," *IEEE Access*, vol. 5, no. 1, pp. 4574–4594, Apr. 2017.
[8] B. Lin, Z. Ghassemlooy, C. Lin, X. Tang, Y. Li, and S. Zhang, "An indoor visible light positioning system based on optical camera communications," *IEEE Photon. Technol. Lett.*, vol. 29, no. 1, pp. 579–582, Apr. 1, 2017.
[9] J. Jiao, F. Li, Z. Deng, and W. Ma, "A smartphone camera-based indoor positioning algorithm of crowded scenarios with the assistance of deep CNN," *Sensors*, vol. 17, no. 4, p. 704, Mar. 2017.
[10] T. Nguyen, A. Islam, and Y. M. Jang, "Region-of-interest signaling vehicular system using optical camera communications," *IEEE Photon. J.*, vol. 9, no. 1, Feb. 2017, Art. no. 7900720.
[11] P. Ji, H. M. Tsai, C. Wang, and F. Liu, "Vehicular visible light communications with LED taillight and rolling shutter camera," in *Proc. IEEE 79th Veh. Technol. Conf.*, May 2014, pp. 1–6.
[12] V. T. B. Tram and M. Yoo, "Vehicle-to-vehicle distance estimation using a low-resolution camera based on visible light communications," *IEEE Access*, vol. 6, pp. 4521–4527, 2018.
[13] H.-W. Chen, S.-S. Wen, Y. Liu, M. Fu, Z.-C. Weng, and M. Zhang, "Optical camera communication for mobile payments using an LED panel light," *Appl. Opt.*, vol. 57, no. 19, pp. 5288–5294, 2018.
[14] S. Shao *et al.*, "An indoor hybrid WiFi-VLC Internet access system," in *Proc. MASS*, Oct. 2014, pp. 569–574.
[15] I.-C. Lu, C.-H. Yeh, D.-Z. Hsu, and C.-W. Chow, "Utilization of 1-GHz VCSEL for 11.1-Gbps OFDM VLC wireless communication," *IEEE Photon. J.*, vol. 8, no. 3, Jun. 2016, Art. no. 7904106.
[16] M. S. Islim *et al.*, "Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED," *Photon. Res.*, vol. 5, no. 2, pp. A35–A43, 2017.
[17] T.-H. Do and M. Yoo, "Performance analysis of visible light communication Using CMOS sensors," *Sensors*, vol. 16, no. 3, p. 309, Feb. 2016.
[18] W. Ding *et al.*, "A hybrid power line and visible light communication system for indoor hospital applications," *Comput. Ind.*, vol. 68, pp. 170–178, Apr. 2015.
[19] H. Ma, L. Lampe, and S. Hranilovic, "Integration of indoor visible light and power line communication systems," in *Proc. IEEE 17th Int. Symp. Power Line Commun. Appl.*, Mar. 2013, pp. 291–296.
[20] R. LaBelle, "Global shutter vs. Rolling shutter readouts," *Biophotonics*, vol. 21, no. 10, pp. 25–28, 2014.
[21] K. Choi, Y. Jang, J. Noh, M. Ju, and Y. Park, "Visible light communications with color and dimming control by employing VPPM coding," in *Proc. ICUFN*, Jul. 2012, pp. 10–12.

DUY THONG NGUYEN received the B.E. and M.S. degrees in telecommunication engineering from the School of Electronics and Telecommunications, Hanoi University of Science and Technology, Vietnam, in 2011 and 2015, respectively. He is currently pursuing the Ph.D. degree in electronic engineering with Kookmin University, South Korea. His research interests include optical camera communications, channel coding, digital signage, and network administration.

SANGCHEOL PARK is currently pursuing the B.S. degree in electronic engineering with Kookmin University, South Korea. His research interests include optical camera communications, wireless networks, visible light communications, and indoor positioning.

YOONSUNG CHAE received the B.S. degree in electronic engineering from Kookmin University, South Korea, in 2016, where he is currently pursuing the M.S. degree in electronic engineering. His research interests include optical camera communications, wireless networks, visible light communications, and indoor positioning.

YOUNGIL PARK received the B.S. and M.S. degrees in electrical engineering from Seoul National University, South Korea, in 1987 and 1989, respectively, and the Ph.D. degree from Texas A&M University, USA, in 1995. He was with Korea Telecom, from 1991 to 1999, in the area of optical communication. He studied high-speed WDM transmission and fiber non-linearity in the fiber network of Korea Telecom. In 1999, he joined Kookmin University, Seoul, where he has been a Professor with the Electronics Engineering Department and served as the Chairman of the Electronics Engineering Department, from 2009 to 2010. He has authored more than 120 journal and conference papers. His research interests include optical communication systems, optical sensors, visible light communication, and sensor networks. Acknowledged by the achievements in this research area, he received the Excellent Research Award from Korea Telecom, in 1997. He is the Winner of paper awards presented at the Photonics Conference Korea, in 2010 and 2011, and at the KICS Conference, in 2011, 2013, and 2015. He is a lifelong member of the Korea Information and Communications Society.