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Visible Light Communication Employing Optical Beamforming: A Review

Sung-Man Kim*

Department of Electronic Engineering, Kyungsung University, Busan, 48434, Korea

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Visible light communication (VLC) is considered a strong future candidate for indoor wireless communication. However, its performance seems to be relatively unsatisfactory when compared to wireless local area network (WLAN) communication using millimeter waves. To improve the performance of VLC, numerous technologies have been proposed so far, in both electrical and optical domains. Among the proposals, optical beamforming (OB) is an optical-domain technology that can concentrate light in a specific direction or on a target spot. It can significantly improve VLC performance and can be widely used, because it does not depend on electrical modulation schemes. Therefore, this review discusses the concept, principle, and types of OB, the structure of a VLC system using OB, performance results of OB, and the combination of OB with electrical signal modulation in VLC. OB is expected to be one of the key techniques in future VLC implementations, similar to radio-frequency beamforming in millimeter-wave communication.

Keywords : Visible light communication, Optical wireless communication, Li-Fi, Optical beamforming
OCIS codes : (060.2605) Free-space optical communication; (200.2605) Free-space optical communication

I. INTRODUCTION

Visible light communication (VLC) is a type of optical wireless communication (OWC) that uses a carrier frequency in the visible region of the spectrum instead of traditional radio frequencies (RF) for carriers. This term is from the viewpoint of wireless-communication researchers, because VLC uses visible light instead of traditional radio frequencies. However, this term could be confusing from the viewpoint of traditional optical-communication researchers, as visible light could be also used in optical-fiber communication (wired communication). Had traditional optical-communication researchers coined a term for this technology, it probably would have been “wireless visible-light communication.”

In recent years, light-emitting diode (LED) technology has progressed rapidly. Owing to high electrical-to-optical power-conversion efficiency, longer lifespan, resistance to impact, and various other advantages, it is expected that LEDs will replace both incandescent and fluorescent bulbs at a rapid pace. Currently, LEDs are widely used for indoor and street lighting, traffic lights, automotive lamps, smart phone lamps, displays, etc. The increase in the usage of LEDs has provided the opportunity for a new kind of wireless communication [1]. Different from the older light bulbs, LEDs can be switched to different light-intensity levels very rapidly. If the switching rate is over 200 Hz, it is perceived as constant light by the human eye, owing to the finite response time of the retina photoreceptors. Beneficially, this characteristic can be exploited for transmitting communication signals. Therefore, LED light could be used for both illumination and communication. This OWC technology using LEDs as light sources is a type of VLC.

Compared to traditional RF wireless communication, VLC has several advantages. First, visible light can be freely used for VLC, whereas conventional RF frequencies are subject to government regulations. Owing to this characteristic, VLC could be an economical solution for indoor communication. Second, VLC does not cause electromagnetic interference (EMI), whereas conventional wireless communication based on RF cause EMI, which is an important problem in specifically sensitive areas such as hospitals and aircraft. Third, the potential bandwidth of VLC communication is incomparably wider than that of conventional RF wireless communication: The bandwidth of visible light is about

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*Corresponding author: sungman@ks.ac.kr, ORCID 0000-0003-1497-6832

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400 THz, whereas most RF wireless communication is below 100 MHz, and millimeter-wave communication is below 10 GHz. Therefore, if the entire bandwidth could be utilized in the future for VLC via wavelength-division multiplexing (WDM), VLC capacity would be much higher than that of conventional RF wireless communication, demonstrating VLC's strong potential. Fourth, VLC usually reuses existing LED lamps already installed for illumination, enabling low installation costs. Fifth, VLC can be easily blocked by a wall, which is an advantage from the security viewpoint, though a disadvantage from the coverage viewpoint. Sixth, even ordinary users can easily identify the ON/OFF state or shadowing of VLC, as visible light is seen by users, whereas it is not easy to identify the strength of an RF signal or shadowing in a given location. Consequently, when a VLC receiver is located in a shadowed region, the user could easily realize the reason for communication failure, and move the VLC receiver to a brighter place.

On the other hand, VLC also has disadvantages. First, if the line-of-sight (LOS) path is blocked by an obstacle, the performance of VLC is not guaranteed. Almost all VLC demonstrations are based on the line-of-sight (LOS) path. Although several researchers have investigated the effect of light reflection in VLC [2-5], they usually considered reflection as interference to the LOS path. It is not easy to demonstrate satisfactory VLC performance utilizing reflected or scattered light. Second, other lamps or sunlight can interfere with VLC. However, it is expected that this interference can be overcome under most indoor conditions, with the development of the VLC technology.

Although VLC has recently attracted considerable attention and a standard was developed in 2011 in the form of IEEE 802.15.7 [6, 7], thus far VLC has not been widely commercialized. One of the primary problems preventing commercialization is that VLC's performance has not surpassed that of WiFi or millimeter-wave communication [8, 9]. Consequently, numerous techniques have been proposed to improve VLC performance. These efforts can be categorized into two parts: electrical- and optical-domain techniques. The electrical-domain techniques include efficient modulation schemes, such as quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM) [10, 11], multiple-input multiple-output (MIMO) [12, 13], pre-/post-equalization [14, 15], etc. Most electrical-domain techniques were originally developed for conventional RF wireless communication, and only later applied to VLC. The optical-domain techniques for improving VLC performance include blue filtering of phosphor-based white LEDs [16], optical MIMO using several LED transmitters and image-sensor or photodiode (PD) array receivers [17, 18], wavelength-division multiplexing (WDM) using RGB LEDs [19], polarization-division multiplexing (PDM) [20], optical beamforming (OB) [21], etc.

As an optical technique, OB focuses the transmitted light on a selected target to significantly increase signal strength. It can be widely utilized because it does not depend on electrical modulation schemes, and significantly improves VLC performance. Just as RF beamforming is one of the key techniques in conventional RF wireless and millimeter-wave communication, OB could be one of the key techniques in future VLC systems. However, only a limited amount of research has been dedicated to OB [1], as this method is not yet well known to VLC researchers. In this context, we review the research on OB-based VLC systems. We discuss the concept, types, and structure of an OB-based VLC system, as well as the performance results of the OB and the combination of OB and electrical signal modulation in VLC systems. This review will enable VLC researchers to easily understand and utilize OB in their work. We believe that this work will contribute to the development of VLC technology.

The rest of the review is organized as follows. In section 2, the concept, principle, and types of the OB are discussed. Since beam steering can be categorized as a type of OB, it is also discussed. However, we do not discuss the beam steering techniques using laser sources, but confine our review to VLC systems based on LED transmitters. In section 3, experimental setups and results for OB-based VLC systems, such as improvement of signal-to-noise ratio (SNR) and transmission distance, are discussed. In section 4, multiple OB access techniques, as well as the concepts and results of time-division multiple-access (TDMA) and space-division multiple-access (SDMA) OB, are discussed. In section 5, a combination of OB with an electrical modulation technique is discussed. These results show that OB can be successfully combined with electrical modulation schemes. In section 6, to enable proper OB operation, an LED-transmitter algorithm for detecting a target device's location in OB-based VLC is discussed. Finally, we conclude this review in section 7.

II. CONCEPT, PRINCIPLE, AND TYPES OF OB

Figure 1 shows the concepts and components associated with a conventional VLC system, side by side with those of a VLC system employing OB. In the conventional VLC system, the LED light spreads out in all directions; therefore, optical signal power decreases with transmission distance. This is also the main reason for VLC performance decrease with distance. To overcome this problem, a VLC system employing OB was proposed, as shown in Fig. 1(b) [21]. OB is a technique that focuses light on a selected target [22], increasing VLC optical signal strength and signal-to-noise ratio (SNR). This enables a VLC system to operate at a higher data rate, by using a higher QAM level.

In Fig. 1(b), it is assumed that a spatial light modulator (SLM) is utilized to realize OB. An SLM is a transparent or reflective optical device that modulates the phase or amplitude of light on each pixel [23]. The modulation on each pixel can be controlled by an electrical signal. Therefore, if a suitable phase modulation is applied, the

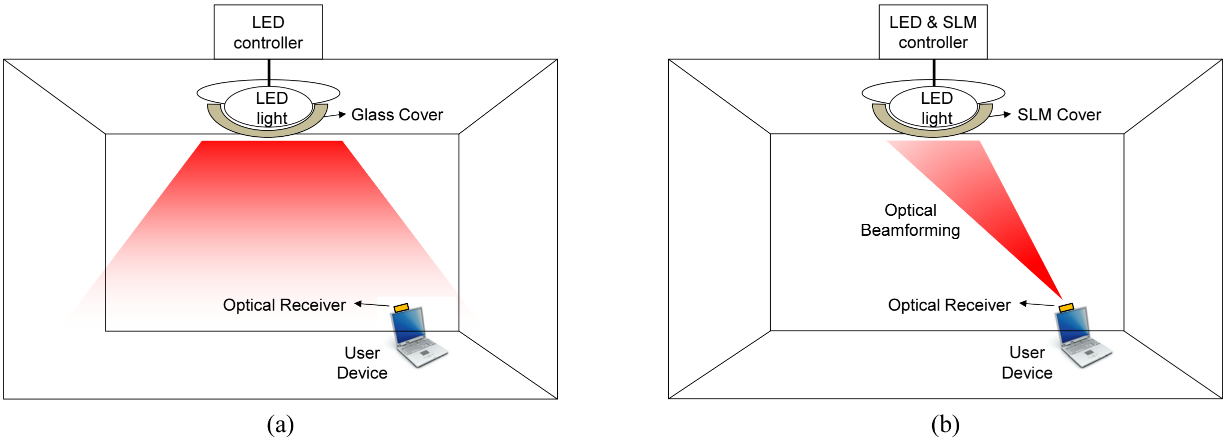


FIG. 1. Block diagram of (a) a conventional VLC system and (b) a VLC system employing OB. The SLM cover in Fig. 1(b) could be replaced by any optical device that can be controlled to focus the light on a selected spot. Indoor application is assumed; figure reproduced from [8].

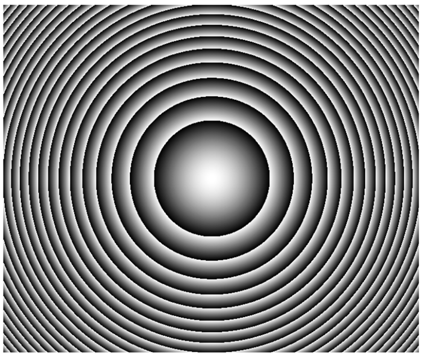


FIG. 2. A Fresnel-lens function's pattern for a SLM; figure reproduced from [21].

SLM can operate as a dynamic diffractive lens. A typical phase-modulation pattern for the SLM is a Fresnel-lens function, which can be displayed as a two-dimensional plot, as shown in Fig. 2. The gray level of the figure indicates the depth of phase modulation on the SLM pixels. The focal length of optical beamforming with a Fresnel lens can be expressed by

$$L = \frac{R_1^2}{\lambda}, \tag{1}$$

where R_1 is the radius of the first circle and λ is the wavelength of the light. The focal point can be controlled by a control computer connected to the SLM, according to the information about the target receiver's location. Here the SLM could be replaced with any device that can be controlled to focus the light on a selected spot.

To date, only a few OB techniques have been proposed for implementation in VLC systems. The first one is the SLM-based OB technique illustrated in Fig. 1 [21]. Another proposed OB technique is based on an optical phased array [24], where the LED light is coupled into a fiber to pass through the optical phased array. The overall signal loss, due to the LED-to-fiber coupling and to other optical devices, is severe; therefore, only simulation results are shown in [24]. The authors of [25, 26] derived the transmission beamforming vectors when multiple LEDs are used to perform OB, when considering intensity modulation and direct detection (IM/DD). However, only simulation results are shown for this technique, and the improvement in performancedoes not seem significant. Among the proposed techniques, the SLM-based OB technique was experimentally demonstrated with an SNR improvement of over 10 dB. Related works such as OB dimming, TDMA OB, SDMA OB, automatic OB algorithm, and combination with OFDM have been reported subsequently [8, 21, 27, 28]. Therefore, we discuss the SLM-based OB in detail later in this review.

III. EXPERIMENTAL SETUP AND PERFORMANCE IMPROVEMENTS BY USING OB

Figure 3 shows an experimental setup of a VLC system employing OB. First, the LED light is directly modulated by a function generator. In other words, a VLC signal is generated by directly modulating the LED, as in conventional VLC systems. The modulating signal could be any type of electrical modulation, such as on-off keying (OOK) or OFDM. The modulated light is sent to a beam expander, to shape the light into a parallel beam. The beam expander can be omitted in a real application if a suitable optical design is interposed between LED transmitter and SLM. Subsequently, the optically parallel, modulated light is passed through a computer-controlled SLM. The control computer sends a phase-modulation pattern to the SLM pixels according to the information about the target device's location. A variation of a two-dimensional Fresnel-lens contour plot can be used as the SLM phase modulation

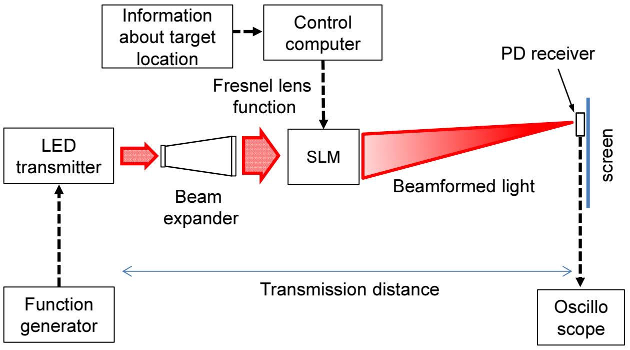


FIG. 3. Experimental setup for a VLC system employing OB; figure reproduced from [21].

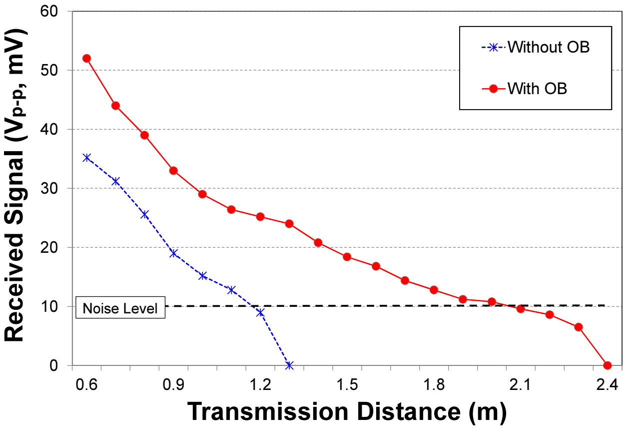


FIG. 4. Received VLC signal amplitudes as a function of transmission distance, with and without OB; figure reproduced from [21].

signal [21]. Owing to the SLM phase modulation, the light is beamformed and focused on the selected target device. The focal point can be controlled by the computer. In [21], the SLM had 800 × 600 pixels with a pixel pitch of 32 × 32 μm. The size of the active area of the SLM was 26.6 × 20.0 mm. The optical phase of the SLM could be modulated at 256 levels with eight control bits.

Here we remark that the VLC signal is generated by modulating the LED light intensity, and the OB is performed by the phase modulation of the SLM. In other words, VLC signal generation and OB are independent processes. Therefore, various electrical modulation formats for VLC can be combined with OB. The modulated (as a VLC signal) and optically beamformed light is received by a PD receiver and further measured by an oscilloscope.

Figure 4 shows the received VLC signal's measured amplitude as a function of transmission distance, with and without OB. It was reported that the maximum transmission distance increased from 110 cm to 200 cm, and that the SNR was improved by up to 12 dB, when employing OB [21]. In other reports, enhancements of bit-error rate (BER) and data rate were also reported [8, 27, 28].

It should be noted that the amount of light allocated to the OB from the total available power can be controlled by changing the modulation depth of the SLM. For example, only 30% of the LED light could be beamformed to a target device, with the remaining 70% not beamformed, being used only for illumination, as the ratio of OB to illumination can be controlled. This function is crucial, especially when the LED light is used for both illumination and VLC, as experimentally demonstrated in [21].

IV. MULTIPLE ACCESS TECHNIQUES WITH OB

In real applications, several user devices could be present in the same room. Therefore, the OB-based VLC system must accommodate multiple user devices, with OB multiple access techniques being required. Therefore, TDMA OB and SDMA OB were demonstrated in [27, 28]. Figure 5 shows the concepts of SDMA and TDMA OB. In SDMA OB, the LED light is divided spatially and focused on each target device with a divided part of light. Thus, each user device can use the VLC continuously. However, the

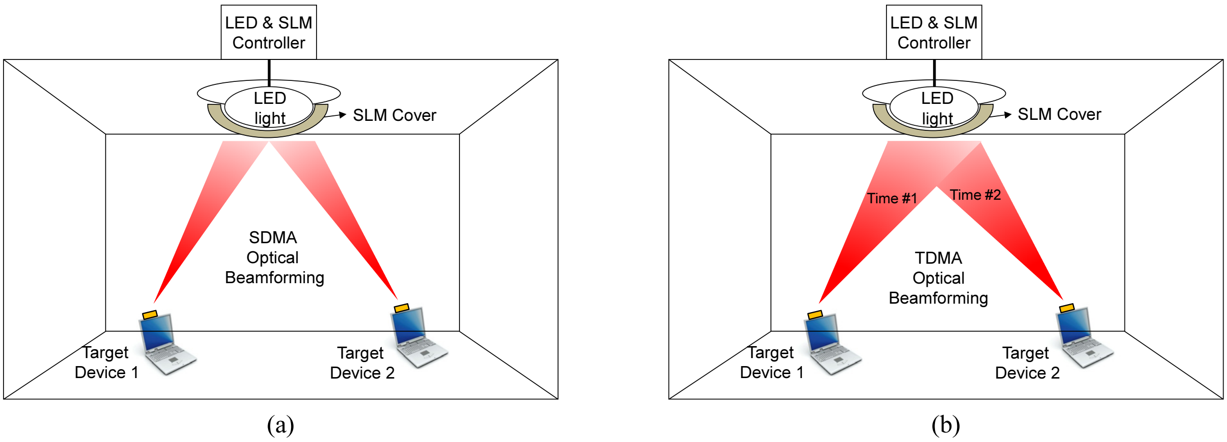


FIG. 5. Concepts of VLC systems with (a) SDMA OB and (b) TDMA OB; figures reproduced from [26, 27].

received VLC signal power is reduced according to the number of user devices. On the other hand, in TDMA OB the entire LED light is focused on each target device, in different time slots. Each user device could use the VLC with the help of TDMA OB. However, the data rate of each user is reduced according to the number of user devices. Here we remark that the maximum frame rate of the SLM is 60 Hz; thus the time slot of TDMA OB should be wider than 1/60 s.

According to the experimental results of [27], the amplitudes of the received VLC signals were increased by 5~10 dB and the transmission distance was almost doubled when employing TDMA OB. According to the experimental results of [28], the amplitudes of the received VLC signals were increased by 8~12 dB and the transmission distance was increased from 90~110 cm to 140 cm when employing SDMA OB.

V. COMBINATION OF OB AND ELECTRICAL SIGNAL MODULATION

One of the important advantages of OB is that it can be combined with any scheme for electrical modulation. To prove this feature, the combination of OFDM plus OB was experimentally demonstrated in [8]. Since phase modulation is not as easy to implement in VLC as in conventional RF wireless communication, IM/DD is widely used in VLC systems. Therefore, in [8] the authors implemented a positive real-valued OFDM signal by using input of Hermitian symmetry in the inverse fast Fourier transform (IFFT) process, and adding a DC value after obtaining the real-valued OFDM signal. A 32-QAM modulation scheme was also utilized in this demonstration.

Figure 6 shows the picture of the experimental setup in [8]. In this demonstration, a laser is used as the light source, instead of an LED. As a laser source is easier to focus using OB, the performance improvement is much more significant than in previous results. Therefore, by using OB, the VLC signal amplitudes increase by 20~25 dB, as shown in [8], with improvements in BER and data rate also being demonstrated. Figure 7 shows the BER data at three distances (100, 185, and 430 cm), with and without OB. When employing OB, the OFDM-based VLC system's data rate increases by up to a factor of 200 at a transmission distance of 430 cm.

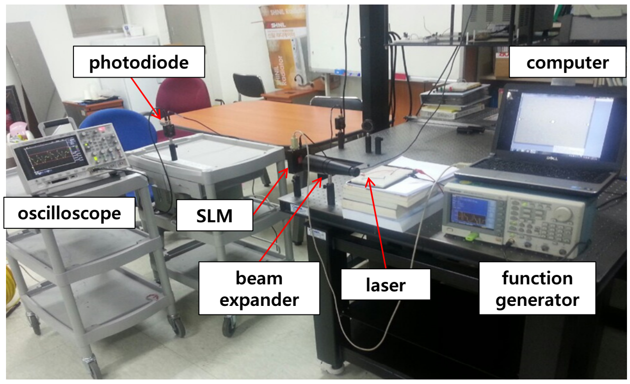


FIG. 6. Photograph of the experimental setup for a VLC system with a combination of OFDM and OB; figure reproduced from [8].

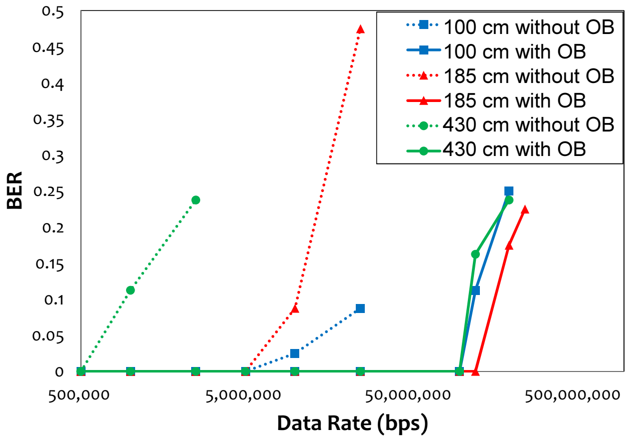


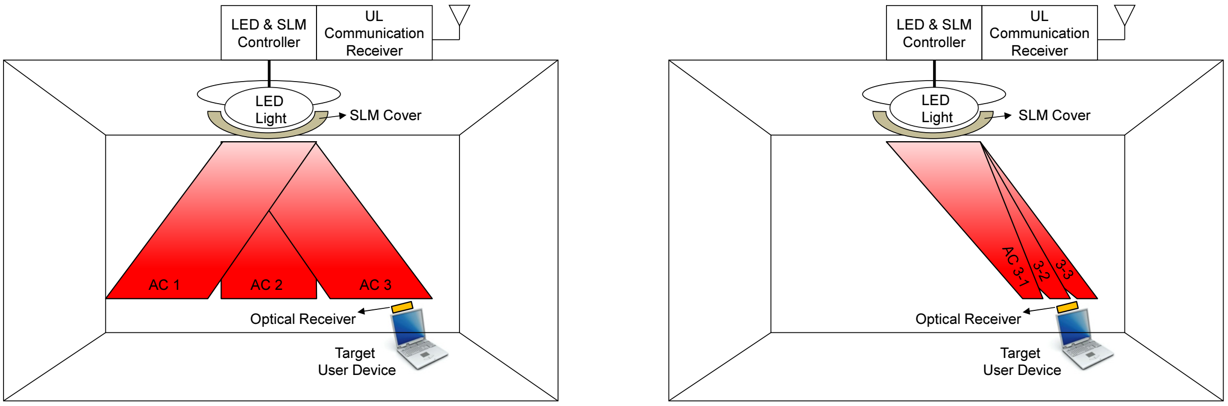
FIG. 7. BER data at transmission distances of 100, 185, and 430 cm, with and without OB; figure reproduced from [8].

VI. AUTOMATIC OB ALGORITHM

To focus the light on a selected user device, the VLC transmitter should acquire the location of the target and implement a method to focus the light on that specific location. To simultaneously solve the two problems, an algorithm suitable for OB was proposed in [21]. Here the availability of an uplink (UL) communication channel between the target device and the VLC transmitter, through conventional RF wireless communication such as Bluetooth or Wi-Fi, is assumed. In the automatic OB algorithm, the concept of an "area code" was proposed. Figure 8 shows an example of the algorithm's implementation.

One of the characteristics of OB is its ability to control the size of the focusing area. At the first stage, the field fully illuminated by the LED light is divided into several areas and numbered with area codes (AC). For example, the fully illuminated field is divided into three areas labeled AC1, AC2, and AC3 in Figure 8. In real applications, the entire field can be divided into tens of areas. The VLC transmitter sends a frame carrying the AC number to each area. The user device will certainly receive one of the frames, thereby identifying its location (AC3 is received in Fig. 8(a)). The user device sends back information about the received AC number to the VLC transmitter through the UL channel.

Subsequently, in a second iteration the VLC transmitter divides the received area into smaller second-step areas, *e.g.* AC3-1, AC3-2, and AC3-3, as illustrated in Fig. 8(b).



(a) (b)

FIG. 8. Procedure of the automatic OB algorithm. Beamformed light with (a) the first-step AC number and (b) the second-step AC number; figure reproduced from [21].

The VLC transmitter sends a frame carrying the second-step AC number to each second-step area, in a procedure similar to that of the first step. Finally, the user device and VLC transmitter will determine the second-step area (AC3-2 in this example) in which the user device is located. After two or more iterations, the VLC transmitter will acquire the exact location of the target, performing the proper OB to the user device.

VII. CONCLUSION

We have reviewed the concept, principle, performance improvements, and other related aspects of OB in VLC systems. OB is an optical-domain technique that focuses the light on a selected target, which could significantly improve the SNR. As OB does not depend on electrical signal modulation, it can be combined with any modulation schemes, thus being useable in a variety of applications. The OB-based VLC system can also accommodate several user devices, by using TDMA or SDMA OB. As the amount of light for OB can be controlled by changing the modulation depth of the SLM, the same LED light could be used for both illumination and communication. By using an algorithm for automatic OB, the LED lighting system could automatically detect a user device's location and properly perform the OB.

Since OB could significantly enhance the performance of VLC systems, it can be widely used in VLC in much the same way that RF beamforming is used in conventional RF communication. However, we think that we need more research on OB, such as the applicable direction and range of OB, maintaining OB power under eye injury, investigating the resolution of OB, finding a more efficient algorithm for automatic OB, etc. If we develop the OB technique more, OB could become one of the key technologies to step up the performance of VLC systems.

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REFERENCES

1. 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. **17**, 2047-2077 (2015).
2. T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Trans. Consumer Electron. **50**, 100-107 (2004).
3. T. Komine, J. H. Lee, S. Haruyama, and M. Nakagawa, "Adaptive equalization for indoor visible-light wireless communication systems," in *Proc. 2005 Asia-Pacific Conference on Communications* (APCC 2005) (Perth, Australia, 2005), pp. 294-298.
4. W. Gu, M. Aminikashani, P. Deng, and M. Kavehrad, "Impact of multipath reflections on the performance of indoor visible light positioning systems," J. Lightw. Technol. **34**, 2578-2587 (2016).
5. C. Chen, D. Basnayaka, and H. Haas, "Non-line-of-sight channel impulse response characterisation in visible light communications," in *Proc. 2016 International Conference on Communications* (ICC 2016) (Kuala Lumpur, Malaysia, May 2016).
6. IEEE Standard for Local and Metropolitan Area Networks-Part 15.7: Short-Range Wireless Optical Communication Using Visible Light, IEEE Std. 802.15.7, Sept. 2011.
7. S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," IEEE Commun. Mag. **50**, 72-82 (2012).
8. S.-M. Kim and K.-K. Kwon, "Optical wireless communication using positive real-valued orthogonal frequency-division multiplexing and optical beamforming," Opt. Eng. **56**, 076105

(2017).

9. T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and J. C. Widmer, “IEEE 802.11ad: directional 60 GHz communication for multi-gigabit-per-second Wi-Fi,” IEEE Commun. Mag. **52**, 132-141 (2014).
10. L. Wu, Z. Zhang, J. Dang, and H. Liu, “Adaptive modulation schemes for visible light communications,” J. Lightw. Technol. **33**, 117-125 (2015).
11. Y. Wang, N. Chi, Y. Wang, R. Li, X. Huang, C. Yang, and Z. Zhang, “High-speed quasi-balanced detection OFDM in visible light communication,” Opt. Express **21**, 27558-27564 (2013).
12. T. Fath and H. Haas, “Performance comparison of MIMO techniques for optical wireless communications in indoor environments,” IEEE Trans. Commun. **61**, 733-742 (2013).
13. Y. Hong, L.-K. Chen, and J. Zhao, “Experimental demonstration of performance-enhanced MIMO-OFDM visible light communications,” in *Proc. Optical Fiber Communications and Exhibition* (OFC) (Los Angeles, USA, March 2017), Th1E.2.
14. X. Li, N. Bamiedakis, X. Guo, J. J. D. McKendry, E. Xie, R. Ferreira, E. Gu, M. D. Dawson, R. V. Penty, and I. H. White, “Wireless visible light communications employing feed-forward pre-equalization and PAM-4 modulation,” J. Lightw. Technol. **34**, 2049-2055 (2016).
15. H. Li, X. Chen, B. Huang, D. Tang, and H. Chen, “High bandwidth visible light communications based on a post-equalization circuit,” IEEE Photon. Technol. Lett. **26**, 119-122 (2014).
16. G. Stepniak, M. Schüppert, and C.-A. Bunge, “Advanced modulation formats in phosphorous LED VLC links and the impact of blue filtering,” J. Lightw. Technol. **33**, 4413-4423 (2015).
17. S.-M. Kim and J.-B. Jeon, “Experimental demonstration of 4 × 4 MIMO wireless visible light communication using a commercial CCD image sensor,” J. Inf. Commun. Converg. Eng. **10**, 220-224 (2012).
18. B, Fahs, M. J. Senneca, J. Chellis, B. Mazzara, S. Ray, J. Ghasemi, Y. Miao, P. Zarkesh-Ha, V. J. Koomson, and M. Hella, “A meter-scale 600-Mb/s 2 × 2 imaging MIMO OOK VLC link using commercial LEDs and Si p-n photodiode array,” in *Proc. Wireless and Optical Communication Conference* (WOCC) (Newark, USA, April 2017).
19. I.-C. Lu, C.-H. Lai, C.-H. Yeh, and J. Chen, “6.36 Gbit/s RGB LED-based WDM MIMO visible light communication system employing OFDM modulation,” in *Proc. Optical Fiber Communications and Exhibition* (OFC) (Los Angeles, USA, March 2017), W2A.39.
20. Y. Wang, C. Yang, Y. Wang, and N. Chi, “Gigabit polarization division multiplexing in visible light communication,” Opt. Lett. **39**, 1823-1826 (2014).
21. S.-M. Kim and S.-M. Kim, “Wireless visible light communication technology using optical beamforming,” Opt. Eng. **52**, 106101 (2013).
22. S.-M. Kim and S.-M. Kim, “Wireless optical energy transmission using optical beamforming,” Opt. Eng. **52**, 043205 (2013).
23. J. Remenyi, P. Varhegyi, L. Domjan, P. Koppa, and E. Lorincz, “Amplitude, phase, and hybrid ternary modulation modes of a twisted-nematic liquid-crystal display at ~400 nm,” Appl. Opt. **42**, 3428-3434 (2003).
24. C. Mekhiel and X. Fernando, “LED beam steering for Li-Fi communications,” in *Proc. IEEE International Workshop on Computer Aided Modelling and Design of Communication Links and Networks* (CAMAD) (Toronto, Canada, Oct. 2016).
25. L. Wu, Z. Zhang, and H. Liu, “Transmit beamforming for MIMO optical wireless communication systems,” Wireless Pers. Commun. **78**, 615-628 (2014).
26. H. Shen, Y. Deng, W. Xu, and C. Zhao, “Rate maximization for downlink multiuser visible light communications,” IEEE Access **4**, 6567-6573 (2016).
27. S.-M. Kim, M.-W. Baek, and S. H. Nahm, “Visible light communication using TDMA optical beamforming,” EURASIP J. Wireless Commun. Networking **2017**, 56 (2017).
28. S.-M. Kim and H.-J. Lee, “Visible light communication based on space-division multiple access optical beamforming,” Chin. Opt. Lett. **12**, 120601 (2014).