

Visible light communication based on space-division multiple access optical beamforming

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We propose and demonstrate a visible light communication (VLC) scheme based on space-division multiple access (SDMA) optical beamforming to accommodate multiple user devices in the VLC based on optical beamforming. SDMA optical beamforming is a technique which separates light-emitting diode light spatially and focuses each part on different target devices simultaneously. We show the experimental results of the VLC signal amplitudes, the optical power densities, and the bit-error rate performance as a function of transmission distance before and after the SDMA optical beamforming. The results show that the VLC signal amplitudes and optical power densities are improved by 8–2 and 3.8–5 dB, respectively, with the help of SDMA optical beamforming.

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Recently, many incandescent light bulbs and fluorescent lamps have been replaced by light-emitting diode (LED) lights because LED lights are more efficient. Besides the high efficiency, LEDs also have another advantage that their light can be modulated with high-frequency signals^[1]. Therefore, they can also be used for optical wireless communications, which is also called visible light communications (VLCs)^[2–5].

VLC has gained much attention as an alternative for future indoor wireless communications because it has several advantages over conventional wireless communications based on radio frequencies (RFs)^[6]. Firstly, VLC does not cause electromagnetic interference. Secondly, visible light can be used freely for VLC applications, whereas most RFs are regulated by government. Thirdly, the potential communication bandwidth of visible light is incomparably wider (~400 THz) than conventional RF communication bandwidth (usually <100 MHz). Fourthly, we can see LED light so that we may recognize whether the VLC system is on or off, whereas we cannot see whether the RFs are on or off.

To improve the performance of VLC, a lot of efforts have been proposed until now. The previous efforts include electrical modulation technologies and optical technologies such as orthogonal frequency division multiplexing^[7], multiple input multiple output^[8], quadrature amplitude modulation (QAM)^[9], equalization^[10], and wavelength division multiplexing^[11].

Recently, a VLC technique based on optical beamforming has been proposed to improve the performance of VLC^[6]. Optical beamforming is a technique to focus LED light on a desired target. It can enhance the data rate by raising the signal-to-noise ratio of the received signal sufficiently for high-level QAM. Because it does not depend on signal modulation formats, it can be widely used in various VLC systems.

However, the previous demonstration of the VLC based on optical beamforming could only communicate with a single target. In the real applications, multiple user devices should be accommodated with the VLC based on optical beamforming. Therefore, we propose and demonstrate a VLC scheme based on space-division multiple access (SDMA) optical beamforming for multiple user devices, which focuses LED light on different targets simultaneously.

Figure 1 shows the structure and concept of the VLC systems based on ordinary optical beamforming and SDMA optical beamforming. Each VLC system consists of a LED light, a spatial light modulator (SLM), and a LED/SLM controller. A SLM is a transparent or reflective optical device which can modulate the phase or amplitude of light on each pixel, and so can be operated as a dynamic diffractive element controlled by electrical signals^[12].

In Fig. 1, we assume a scenario of two user devices. As shown in Fig. 1(a), the VLC system based on ordinary optical beamforming can accommodate only a single target. However, in the real applications, multiple user devices should be accommodated. Therefore, we propose a VLC technique based on SDMA optical beamforming (Fig. 1(b)), which focuses LED light on different targets simultaneously. The VLC technique based on SDMA optical beamforming divides LED light spatially and focuses each part on different target devices.

Figure 2 shows block diagram of the experimental setup for the VLC system based on SDMA optical beamforming. Figure 3 shows the picture of the real experimental setup. In Fig. 2, a LED transmitter is modulated by a pseudo-random binary signal of 30 kb/s. The modulation signal format is non-return-to-zero. After the LED transmitter, the beam expander is

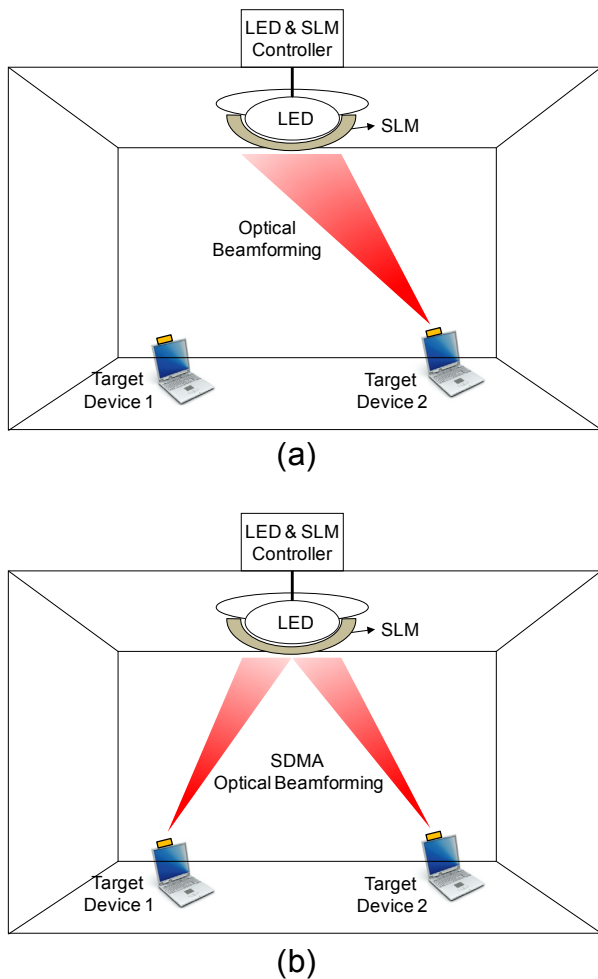


Fig. 1. Structure and concept of the VLC systems based on (a) ordinary optical beamforming and (b) SDMA optical beamforming.

used to control the beam size of the transmitted light and form it into a parallel ray. If the optical design of the LED transmitter is optimized, the beam expander can be omitted in the real application. After passing through the beam expander, the transmitted light goes into a SLM, which has 800×600 translucent liquid crystal pixels with a pixel pitch of $32 \mu\text{m}$. The size of

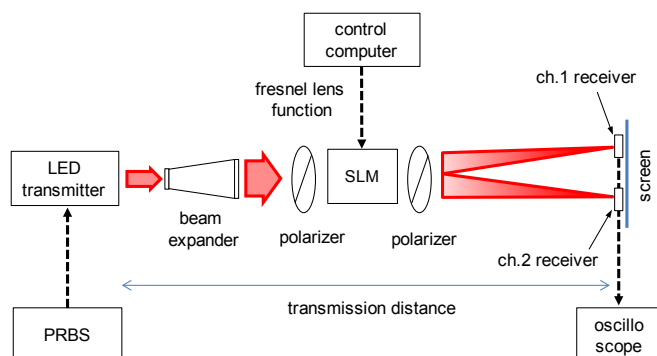


Fig. 2. Block diagram of experimental setup.

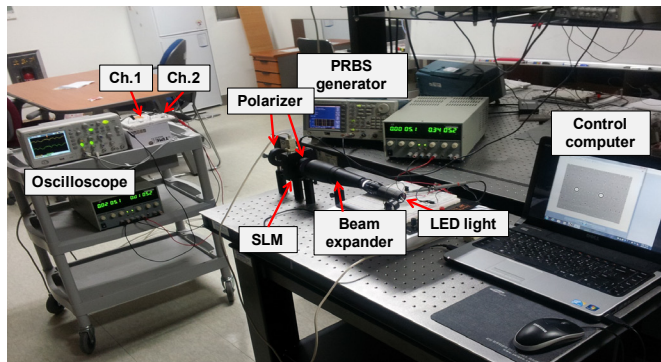


Fig. 3. Picture of experimental setup.

the active area in the SLM is 26.6×20.0 (mm). The SLM model used in the experiment requires polarizers before and after the SLM to enhance the performance of phase modulation. The SLM can modulate the phase of the light on each pixel with 256 levels. Then, a Fresnel lens function is applied to the SLM to operate the SLM as a dynamic diffractive lens. After passing through the SLM, the light is beamformed and focused on target devices. In this experiment, two target devices are considered.

Figure 4 shows a contour plot of the phase modulation used in the SLM. In Fig. 4, the black and white colors mean the phase transition on the pixel. The separation distance between the two circle centers is 14 mm in the SLM. The contour plot of phase modulation in Fig. 4 has two Fresnel lens functions and so makes two focal points for two target devices. The focal length of a Fresnel lens function is given by

$$L = R_1^2 / \lambda, \quad (1)$$

where R_1 is the radius of the first circle in the Fresnel lens function and λ is the wavelength of the light. The focal points are controlled by a control computer according to information of the locations of the two target devices. In Fig. 4, the left part of the LED light is focused on one target device (Ch.1) and the right part of the LED light is focused on the other target device (Ch.2).

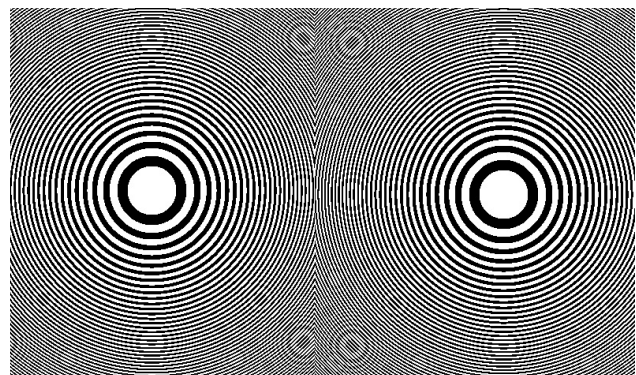


Fig. 4. Contour plot of the phase modulation in the SLM.

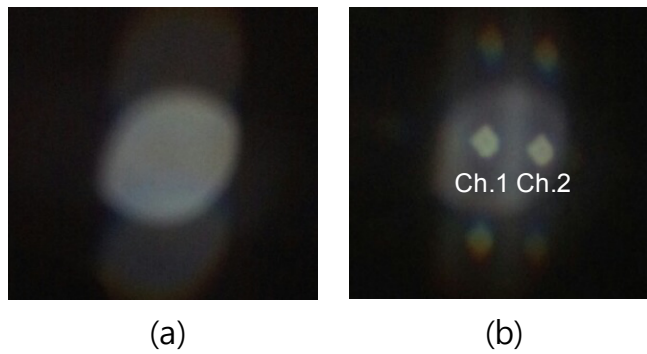
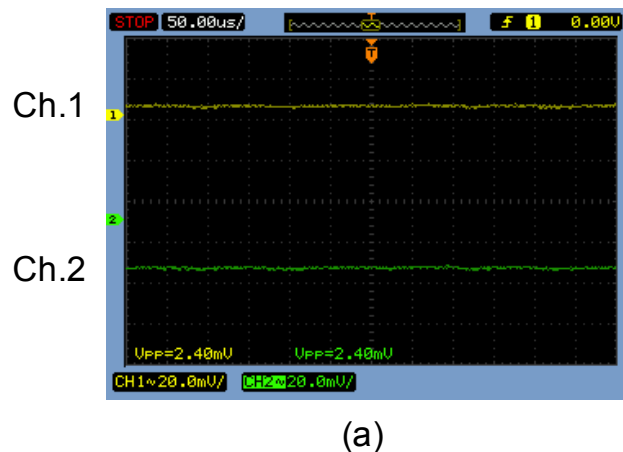
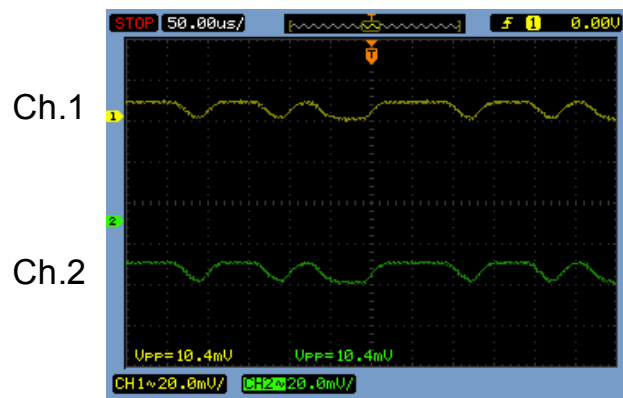


Fig. 5. Experimental results on the screen (a) before and (b) after SDMA beamforming.

Figure 5 shows the experimental results on the screen before and after SDMA optical beamforming at a transmission distance of 110 cm. Because the LED light after the beam expander is a parallel ray, the optical footprint size is similar to the SLM active area. In Fig. 5(b), two points are focused on the screen after the SDMA optical beamforming. The spacing between the two channels is 14 mm. The faint pattern outside the main bright area is due to the diffraction of two-dimensional pixel matrix of the SLM. It should be



(a)



(b)

Fig. 6. Received VLC signals (a) before and (b) after SDMA optical beamforming.

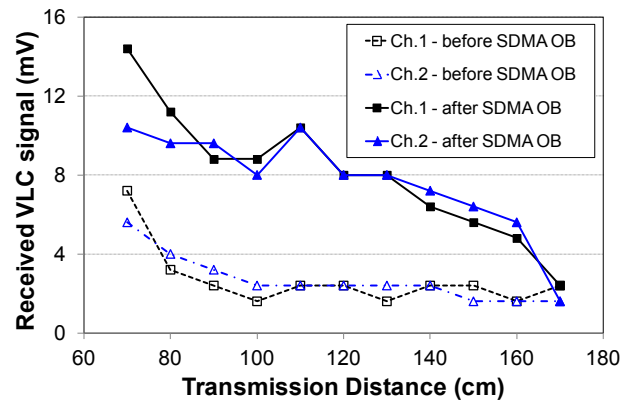


Fig. 7. Amplitudes of the VLC signals of the two channels as a function of transmission distance. SDMA OB, SDMA optical beamforming.

noted that the SLM model used in the experiment cannot operate as a perfect phase modulator, so the unmodulated light is still seen on the screen even after the optical beamforming.

Figure 6 shows the received VLC signals on Ch.1 and Ch.2 before and after SDMA optical beamforming at a transmission distance of 110 cm. Note that Fig. 6 shows the averaged signal waveform to reduce noise. The amplitudes of VLC signals on the two channels increase after the SDMA optical beamforming. Although the peak-to-peak amplitude is 2.4 mV before the SDMA optical beamforming, it increases to 10.4 mV after the SDMA optical beamforming in both channels. Therefore, the signal amplitude increases by more than four times with the SDMA optical beamforming.

To investigate the performance improvement of SDMA optical beamforming, the VLC signal amplitudes of the two channels before and after the SDMA beamforming are measured as a function of transmission distance (Fig. 7). The results show that amplitudes of the received VLC signals of both the channels are improved by 8–12 dB in the transmission distance of 80–160 cm thanks to the SDMA optical beamforming.

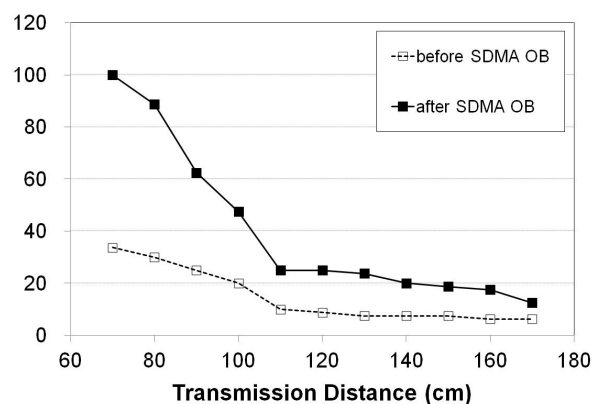


Fig. 8. Optical power density at the two channels as a function of transmission distance. SDMA OB, SDMA optical beamforming.

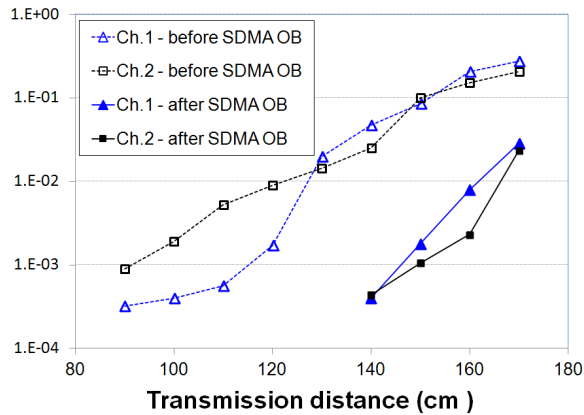


Fig. 9. BER performance as a function of transmission distance.

Therefore, both the channels can enjoy the benefit of optical beamforming simultaneously.

We also measured the received optical power density at the receivers as a function of transmission distance before and after the SDMA beamforming (Fig. 8). Because the received optical powers at the two channels are equal, only one line is plotted before and after the SDMA beamforming. It is shown that the optical power density increases with the help of the SDMA optical beamforming. In the experimental results, the optical power density increases by 3.8–5 dB in the transmission distance of 80–160 cm thanks to the SDMA optical beamforming. These results correspond to the results in Fig. 7 since electrical gain is twice that of optical gain in decibels due to the square-law detection of photodiodes.

Figure 9 shows the bit-error rate (BER) performance of the VLC before and after the SDMA optical beamforming. If we define a BER of $<10^{-3}$ as a criterion for successful transmission, the transmission distance is improved from 90–110 to 140 cm with the help of SDMA optical beamforming. It should be noted that the SDMA optical beamforming technique costs a SLM. However, it is expected that the price of a SLM can be down to a same size liquid crystal display because their

hardware is quite similar. It should be also noted that a SLM has a little optical loss even though the gain of SDMA optical beamforming is higher than the loss.

In conclusion, we propose and demonstrate a VLC scheme based on SDMA optical beamforming to accommodate multiple users in the VLC systems based on optical beamforming. Our results show that multiple devices can enjoy the benefit of optical beamforming simultaneously, with the SDMA optical beamforming. Since SDMA optical beamforming technique does not depend on the modulation format and can enhance the performance of VLC in multiple user devices, it can be widely used in VLC.

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