# High Speed RGB Visible Light Communication (VLC) Using Digital Power-Domain Multiplexing (DPDM) of Orthogonal Frequency Division Multiplexed (OFDM) Signals

**Wahyu Hendra Gunawan[1, 2], Yun-Han Chang[1, 2], Chi-Wai Chow[1, 2*], Yang Liu[3], and Chien-Hung Yeh[4]**
[1]*Department of Photonics, College of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan*
[2]*Department of Photonics, College of Electrical and Computer Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan*
[3]*Philips Electronics Ltd., N.T., Hong Kong*
[4]*Department of Photonics, Feng Chia University, Seatwen, Taichung 40724, Taiwan*
*cwchow@faculty.nctu.edu.tw

**Abstract:** We experimentally demonstrate a record 21 red-green-blue (RGB) laser-diode (LD) visible-light-communication (VLC) using digital-power-domain-multiplexing (DPDM) of orthogonal-frequency-division-multiplexed (OFDM) signals. 21.01-Gbit/s RGB DPDM-OFDM VLC transmission is achieved. © 2022 Author(s)
OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications

## 1. Introduction

Visible light communication (VLC) is a promising technology for the future wireless communication systems [1]. It is a kind of optical wireless communication (OWC) using visible light spectrum for communication. Due to the low deployment cost, high privacy, immunity to radio-frequency (RF) electromagnetic interference (EMI), unlicensed communication spectrum, OWC and VLC have been considered as a potential candidate for the beyond 5G or 6G mobile and wireless communication. Orthogonal frequency division multiplexing (OFDM) is widely used in VLC due to its high spectral efficiency and robustness against interference between symbols. Besides, wavelength division multiplexing (WDM) can be used to increase the VLC transmission capacity. Recently, there are many studies of OFDM based VLC systems using light emitting diode (LED). Cossu *et al* reported a 3.4 Gbit/s red green blue (RGB) LED based WDM VLC system [2]. Beside, Chi *et al* also reported a 3.375 Gbit/s RGB LEDs based WDM VLC system using 8-level pulse amplitude modulation (PAM8) signal [3]. To reduce the LED efficiency droop and increase the transmitter (Tx) modulation bandwidth, laser diode (LD) can be employed for the VLC systems. Wu *et al* demonstrated a 8 Gbit/s VLC system using RGB LDs [4]; and Wei et al demonstrated a 20.231 Gbit/s WDM RGB LD bidirectional VLC system using OFDM with bit loading algorithm [5]. Besides the physical domain multiplexing schemes, such as WDM, digital power domain multiplexing (DPDM) scheme can also be used to enhance the total system capacity.

In this work, we propose and experimentally demonstrate for the first time up to the authors' knowledge 20.01 Gbit/s RGB VLC system using DPDM OFDM signal, fulfilling the pre-forward-error-correction bit-error-rate (pre-FEC BER = $3.8 \times 10^{-3}$) threshold. DPDM is inspired by the work [6], in which it is related to power domain multiplexing for multiple users or multiple receivers (Rx). Here, the DPDM OFDM signal can enhance the total system capacity by allowing an acceptable signal spectra overlapping among different power division signals to maximize the bandwidth utilization. By employing the successive interference cancellation (SIC) at the Rx, the independently multiplexed signals can be retrieved. Unlike the bit and power loaded OFDM signal, the proposed DPDM OFDM does not need to adaptively adjust the quadrature amplitude modulation (QAM) modulation level and power level of each OFDM subcarrier for channel estimation. Experimental results show that the proposed DPDM OFDM RGB VLC system performs slightly better than the bit-loaded OFDM RGB VLC system [5]. Here, the modulation and demodulation of the DPDM OFDM are discussed. The optimum power levels of the individual signals in DPDM are also analyzed.

## 2. DPDM Algorithm and Experiment

Without loss of generality, we show the DPDM mechanism by assuming that the data is divided into two individual signals, $x_i$, where $i$ = 1 and 2. The corresponding transmission powers are $P_i$, where $i$ = 1 and 2. In each wavelength channel, the sum of total power $P_i$ is equal to $P$. The transmitted signal is shown in Eq. (1).

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 \tag{1}$$

The received signal can be illustrated in Eq. (2),

$$y_i = h_i x + n_i \tag{2}$$

where $h_i$ and $n_i$ represent the channel response and noises. As shown in Eq. (1), different individual DPDM signals should maintain a certain power ratio for the successful decoding. At the Rx, the SIC process is performed and the decoding priority is based on the order of the increasing channel gain. In the example of 2 individual signals, Data 2 and Data 1 with $P_2 > P_1$, $x_2$ signal will be recovered first without the need of SIC since it has higher power than $x_1$. Then the decoded $x_2$ will be employed to obtain $x_1$ in SIC process [6] by subtracting itself from the received signal. Based on the Shannon-Hartley equation about the channel capacity $C$, which is equal to the channel bandwidth $B$ times the logarithm of one plus signal signal-to-noise ratio (SNR). Hence, the total capacity of the PDPM signal is illustrated in Eq. (3). The total channel capacity $C$ is equal to the capacities of the two individual signals $C_2$ and $C_1$. The channel responses of individual Data 2 and Data 1 are $h_2$ and $h_1$ respectively. Since there is only one Tx and one Rx, the Data 2 and Data 1 share the same bandwidth $B$ and noise power $P_N$. From Eq. (3), we can observe that for Data 2, the capacity $C_2$ is limited by the transmission noise $P_N$ plus the interference from the Data 1. While for Data 1, the capacity $C_1$ is limited by $P_N$ only.

$$\begin{aligned} C &= C_2 + C_1 \\ &= B\log_2\left(1+\frac{|h_2|^2 P_2}{|h_1|^2 P_1 + P_N}\right) + B\log_2\left(1+\frac{|h_1|^2 P_1}{P_N}\right) \end{aligned} \tag{3}$$

Fig. 1 shows the principle of encoding and decoding of the proposed RGB VLC system. Here, we use the red LD channel as an example. At the Tx side, two individual data signals (Data 1 and Data 2) are first mapped to quadrature phase shift keying (QPSK) formats. Then the signals are allocated to subcarriers according to channel conditions. After this, the two signals at different power levels are combined with superposition code (SC) via DPDM. Hence the constellation diagrams are shaped according to the power allocation. This can be implemented by multiplying the signals by specified power levels $P_1$ or $P_2$. After this, traditional OFDM encoding is employed, including inverse fast Fourier transformation (IFFT), parallel-to-serial (P/S) conversion and cyclic prefix (CP) insertion. After the DPDM OFDM signal is generated, it is applied to a LD via a digital-to-analog converter (DAC). In the experiment, the DAC is an arbitrary waveform generator (AWG, Tektronix® AWG 70001). Then, the RGB channels have the wavelength of 640 nm, 520 nm, and 450 nm. They are multiplexed by dichroic mirrors (DMs). After a 1 m free-space transmission distance, the WDM RGB signal will be separated by using DMs. Each wavelength channel is received by a PD (EOT ET-2030A) attached to a real-time oscilloscope (RTO, Teledyne LeCroy® 816ZI-B), which acts as an analog-to-digital converter (ADC). After the ADC, serial-to-parallel (S/P) conversion is performed to retrieve the information in subcarriers. Zero-forcing scheme is used to restore the signal after the channel, and fast Fourier transform (FFT) is used to convert it into frequency domain. In the DPDM decoding, Data 2 will be decoded first while regarding Data 1 as noise, so direct QPSK demodulation can be applied. Then, SIC is applied to subtract the retrieved Data 2 from the main signal before the QAM demodulation applied. After this, FFT and QPSK demodulation are used to retrieve the Data 1. Here, the FFT size is 512 and CP is 32.

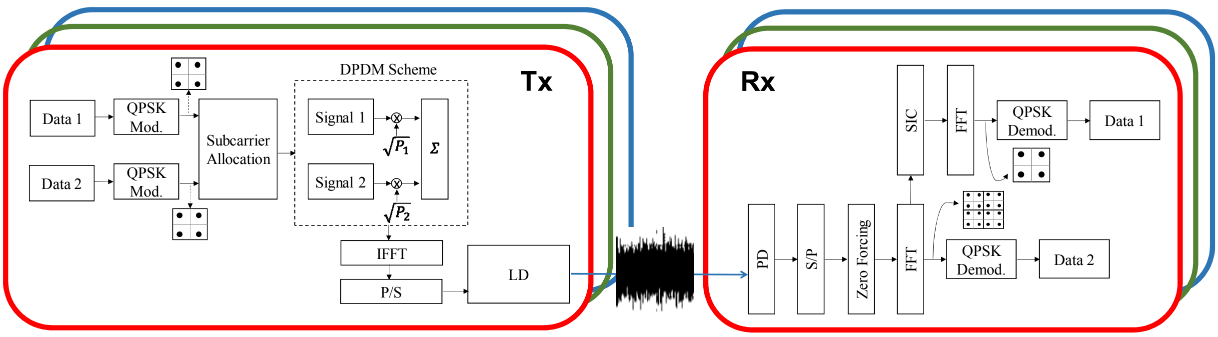


Fig. 1. Architecture of the proposed RGB VLC system using DPDM OFDM signal.

## 3. Results and Discussion

Since in each of the RGB wavelength channel, there are two individual data signals superimposed in power domain and the constellation diagrams are shaped according to the power allocation, it is important to obtain the optimum power ratio to maximize the system throughput and to minimize the BER of both data. To simple the DSP of Tx and Rx, the power ratio is applied to all the subcarriers. The measurement of the BER against power ratio of Data 1 and Data 2 of the DPDM scheme shows the optimum power ratio is 4 dB. Figs. 2(a)-(c) show the measured BER curves of the two individual signals and combined DPDM signals for the R, G, and B channels respectively. We can observe that the maximum data rate achieved by the DPDM signal fulfilling the pre-FEC BER limit is 8.07 Gbit/s at the BER $1.7 \times 10^{-3}$ for red channel, 6.62 Gbit/s at the BER $3.72 \times 10^{-3}$ for green channel, and 6.32 Gbit/s at the BER $2.1 \times 10^{-3}$ for blue channel. Fig 3(a) shows the measured SNRs of the two individual signals (Data 1 and Data 2) over all OFDM subcarrier for R, G, and B channels in the proposed DPDM OFDM system. Fig. 3(b)-(d) shows the correspond constellation diagrams for Data 1 and Data 2 for RGB channels. Here, the total data rate of the system is 21.01 Gbit/s.

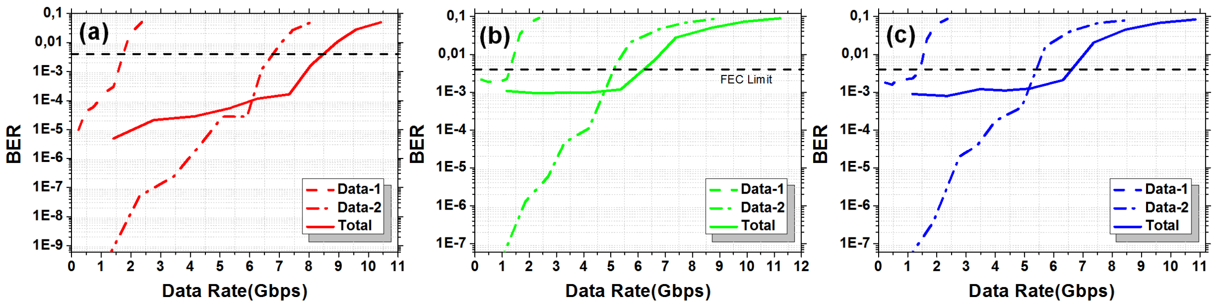


Fig. 2. (a) Measured BER curves of the two individual signals and the DPDM signals for (a) R channel, (b) G channel, and (c) B channel.

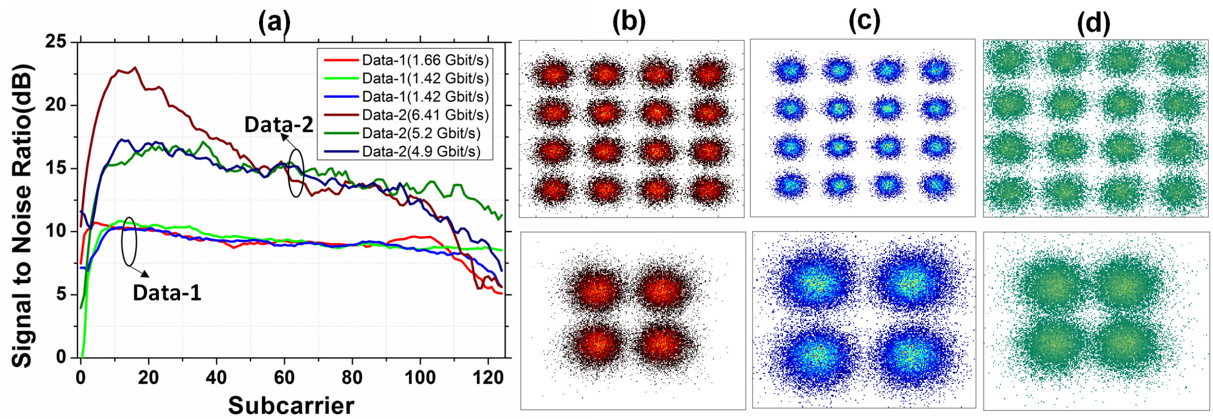


Fig. 3. (a) Measured SNRs of the two individual signals (Data 1 and Data 2) over all OFDM subcarrier for red, green, and blue channels in the proposed DPDM OFDM system. (b)-(d) the constellation diagrams for Data 2 (16 QAM) and Data 1 (4 QAM).

## 4. Conclusion

We proposed and experimentally demonstrated for the first time up to the authors' knowledge a 20.01 Gbit/s RGB VLC system using DPDM OFDM signal, fulfilling the pre-FEC BER threshold. Here, the DPDM OFDM signal can enhance the total system capacity by allowing an acceptable signal spectra overlapping among different power division signals to maximize the bandwidth utilization. Here, the modulation and demodulation of the DPDM OFDM were discussed.

**Acknowledgment** This work was supported by the Ministry of Science and Technology, Taiwan, MOST-110-2221-E-A49-057-MY3, MOST-109-2221-E-009-155-MY3 and Ministry of Education (MOE) in Taiwan

## 5. References


[1] C. W. Chow, et al, "Enabling techniques for optical wireless communication systems," Proc. OFC 2020, M2F.1. (Invited)
[2] G. Cossu, et al, "3.4 Gbit/s visible optical wireless transmission based on RGB LED", Opt. Exp. **20**, B501–B506 (2012).
[3] N. Chi, et al, "3.375-Gb/s RGB-LED based WDM visible light communication system employing PAM-8 modulation with phase shifted Manchester coding," Opt. Exp. **24**, 21663-21673, (2016).
[4] T. C. Wu, et al, "Tricolor R/G/B laser diode based eye-safe white lighting communication beyond 8 Gbit/s," Sci. Rep. **7**, 11 (2017).
[5] L. W. Wei, et al, "20.231 Gbit/s tricolor red/green/blue laser diode based bidirectional signal remodulation visible-light communication system," Photon. Res. **6**, 422-426 (2018).
[6] Y. Saito, et al, "Non-orthogonal multiple access (NOMA) for cellular future radio access," Proc. VTC Spring, 2013, pp. 1-5