# A Real-time High-speed Visible Light Communication System Based on RGB-LEDs

Zhi Li*, Chao Zhang*, Dedong Sun†, Hui Yang*, and Jian Song*‡
*Tsinghua National Laboratory of Information Science and Technology
Department of Electronic Engineering, Tsinghua University, Beijing 100084, P.R. China
†State Grid Information & Telecommunication Group Co. Ltd., Beijing 102209, P.R. China
‡Shenzhen City Key Laboratory of Digital TV System
(Guangdong Province Key Laboratory of Digital TV System), Shenzhen 518057, P. R. China.
zhili15@mails.tsinghua.edu.cn, z_c@tsinghua.edu.cn, sundedong@sgitg.sgcc.com.cn

***Abstract*—A real-time high-speed visible light communication (VLC) system based on RGB-LEDs is proposed in this paper. With the use of the wavelength-division multiplexing (WDM), the system enables three individual color channels. The physical layer of the system is based on time-domain synchronous OFDM (TDS-OFDM) technology. Digital pre-distortion method also is applied to improve the SNR performance. Experiment demonstration shows that the proposed system can achieve a peak transmission data rate of 544.32 Mbps in real time with 256-order constellation, transmitting three individual 4K ultra-high-definition television (UHDTV) signals at the same time. The proposed system is proven to be sufficient for wireless indoor multimedia communication requirements.**

***Index Terms*—Visible light communication, WDM, real-time, wireless indoor multimedia communication.**

## I. Introduction

In recent years multimedia transmission technology has made rapid developments, meeting the growing demand for multimedia transmission services. However, wireless indoor multimedia communication (WIMC) still faces enormous challenges [1]. WIMC systems need to be both real-time and high-speed, while solving the problem of scarce spectrum resources.

With the advantages of high transmission data rate, the absence of electromagnetic interference, and saving spectral resources, visible light communication (VLC) technology has greatly developed during the past few years as an emerging wireless communication technology, and is considered to be one of the best choices for WIMC. VLC is perfectly suitable for various types of indoor environments, including libraries, electronic equipment factories, airports, and hospitals. Moreover, VLC technology can be applied directly onto the existing lighting devices with little modification, reaching the convenience of both illumination and wireless communication [2] [3].

In a VLC system, light emitting diodes (LEDs) have been widely used as the lighting and signal sources [3]. LEDs have the advantages of low power consumption, long lifetime and high brightness, making LEDs suitable for optical wireless communication in indoor environments. A photo detector (PD) is usually used as a receiver in VLC systems. Since the optical signal in a VLC system must be both real and non-negative, the signal is transmitted using intensity modulation (IM) at the sender, and is detected using direct detection (DD) at the receiver, which is called an IM/DD system [4]. The light sources convert the electric signals to optical signals, which is received and recovered to electric signals by the PDs at the receiver sides.

Compared with relatively simple modulation methods such as on-off keying (OOK) and pulse-position modulation (PPM), orthogonal frequency division multiplexing (OFDM) is considered to be one of the best modulation techniques for optical wireless communication, with the advantages of resistance to channel multi-path, high spectral efficiency and low complexity equalization at the receiver [5]. The baseband complex signal is adjusted to be both real and non-negative when OFDM is utilized in a VLC system to fit the IM/DD requirements. Based on different types of guard intervals for OFDM schemes, cyclic prefix OFDM (CP-OFDM), zero padding OFDM (ZP-OFDM) and time-domain synchronous OFDM (TDS-OFDM) have been widely used in different systems. In digital television terrestrial multimedia broadcasting-advanced (DTMB-A) standard, dual PN padding TDS-OFDM is applied, which leads to a low-complexity equalization, and improves the channel estimation accuracy [6].

The data rates of recent VLC systems are increasing rapidly. Research reports have demonstrated numerous high-speed VLC systems. So far, the OFDM VLC wireless communication system with a transmission rate up to 11.1 Gbps has been utilized, indicating the infinite potential of VLC technology [7]. However, most of the high-speed VLC systems are offline-processed rather than real-time [8], limiting its wide applicability. In [9], a real-time visible light communication system based on 2ASK-OFDM coding is proposed, reaching a speed up to 76 Mbps. In [10], a real-time VLC system using bidirectional rate-adaptive OFDM transmission reaches a data rate of 200 Mbps. The aforementioned systems are not sufficient to meet the requirements of WIMC.

In this paper, a real-time high-speed VLC system is proposed, which is based on red, green and blue (RGB) LEDs using wavelength-division multiplexing (WDM) method. The system proposed is able to realize the real-time transmission of high-speed multimedia signals, reaching a transmission data rate higher than 500 Mbps. The system structure is analyzed

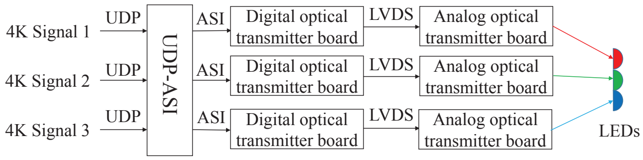


Fig. 1. Block diagram of the optical transmitter.

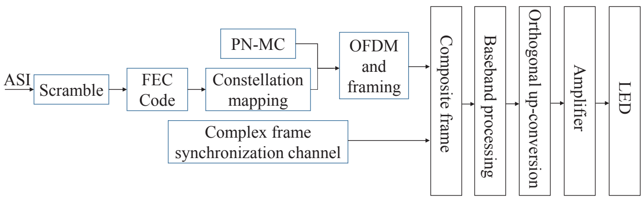


Fig. 2. Block diagram of the optical transmitter for one single color.

in detail, and the demonstration results are provided in this paper. It will be a very promising technology for WIMC.

## II. System Description

Fig. 1 shows the block diagram of the optical transmitter of the proposed system. The light sources contain three individual colors, including red, green and blue. WDM method is utilized with RGB-LEDs [10], providing three individual color channels. For a single color channel, a 4K ultra-high-definition television (UHDTV) signal is transformed from User Datagram Protocol (UDP) stream to asynchronous serial interface (ASI) stream. The signal is then modulated and channel coded through the digital optical transmitter board. The output low-voltage differential signaling (LVDS) intermediate frequency (IF) digital signal then passes through the analog optical transmitter. The block diagram of the optical transmitter for one single color is shown in Fig. 2.

In the optical transmitter, the signal needs to be scrambled by pseudo-noise (PN) sequence firstly. Low density parity check code (LDPC) is applied in the channel coding module. In the proposed system, the code rate of the LDPC code is 1/2, and the code length is 15360 bits. The 256 amplitude phase shift keying (APSK) constellation with Gray mapping (Gray-APSK) used in DTMB-A system [11] is applied, which is shown in Fig. 3. If the receiver is moving or the diffuse reflection is strong, lower order modulations including 16-APSK and 4-APSK can also be selected. Time-domain synchronous OFDM (TDS-OFDM) technique is adopted in the physical layer, with inserted dual PN padding sequences as the guard interval [12]. Then, the baseband modulated complex signal is quadrature up-converted to a low IF frequency, and a suitable DC-bias is added, making the signal both real and non-negative for the IM/DD system. After being digital-to-analog (D/A) converted and passing through a low pass filter (LPF), the signal then drives the LED sources.

The dual PN padding TDS-OFDM scheme is applied in the proposed system, the frame structure of which is shown in Fig. 4. Two identical PN sequences are denoted as $\mathbf{p}_i^1 = \mathbf{p}_i^2 = [p_0, p_1, \cdots, p_{\mathrm{M}-1}]$, where $M$ is the length of the PN sequence, and $i$ is the frame index. $\mathbf{S}_i$ is the frame data with a length of $N$. Thus the length of one frame is $N + 2M$. Inter-symbol-interference (ISI) caused by multi-path effect should be eliminated at the receiver. Since $\mathbf{p}_i^2$ is only effected by $\mathbf{p}_i^1$ through multi-path fading channel, the channel estimation can be achieved easily, without iterative methods. While having the advantages of OFDM technology, the dual PN padding TDS-OFDM scheme can reduce the complexity of the receiver greatly, with a ignorable slight decrease in the spectrum efficiency.

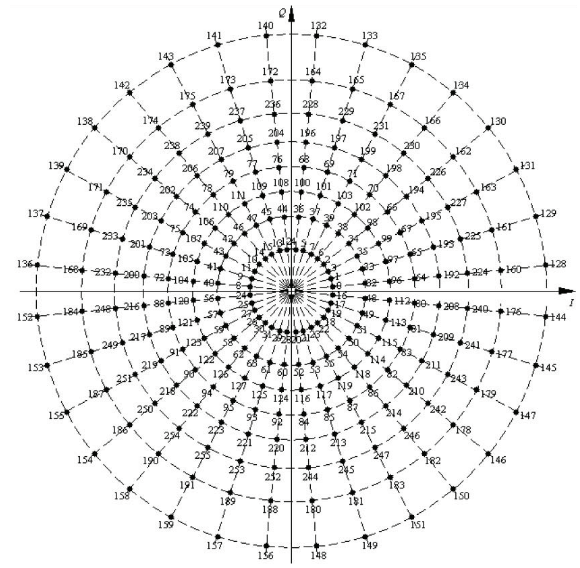


Fig. 3. 256 APSK constellation mapping.

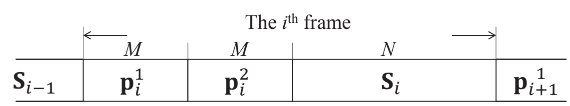


Fig. 4. Frame structure with dual PN padding sequences.

In DTMB-A standard, APSK constellation with Gray mapping is applied. As is shown in Fig. 3, for 256 APSK constellation mapping, there are 8 rings in the constellation and each of which contains 32 points. Each point on the same ring has identical initial phase. The constellation diagram of APSK is more similar to the Gaussian distribution, so from the information theory point of view, APSK achieves better channel capacity. Compared with quadrature amplitude modulation (QAM) with Gray mapping (Gray-QAM), Gray-APSK provides better shaping gain in both independent and iterative de-mapping scenarios, which makes Gray-APSK a better choice for the system proposed in this paper [11].

Since most of the commercial LEDs have a great attenuation with the frequency increasing in the used frequency range, a digital pre-distortion technology is applied to increase the response for the high frequency side [13], making the received spectrum flat and ensuring a relatively high signal-to-noise


Fig. 5. Spectrum of the received signal without pre-distortion: blue curve. Spectrum of the received signal with pre-distortion: yellow curve.

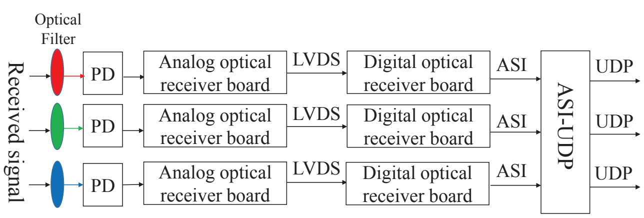


Fig. 6. Block diagram of the optical receiver.

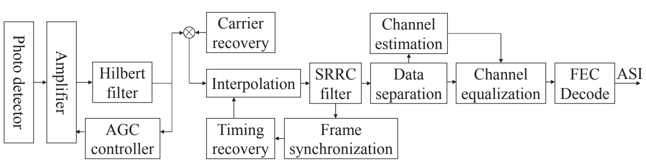


Fig. 7. Block diagram of the optical receiver for one single color.

TABLE I
SYSTEM PARAMETERS

| Parameter | Value |
|---|---|
| Working band | 2-26 MHz |
| Effective bandwidth of one coloer | 22.68 MHz |
| Total equivalent effective bandwidth | 68.04 MHz |
| Modulation | TDS-OFDM |
| Guard interval | Double PN-MC256 |
| FFT length | 4096 |
| FEC code rate | 1/2 |
| FEC code length | 15360 |
| Red light wavelength | 630 nm |
| Green light wavelength | 520 nm |
| Blue light wavelength | 450 nm |

ratio (SNR). Fig. 5 indicates the spectrum of the received signal with and without pre-distortion.

Fig. 6 illustrates the block diagram of the optical receiver of the proposed system, which is directly corresponding to the transmitter. Firstly, the received optical signal is separated into individual RGB colors by different optical filters, and is

TABLE II
SYSTEM CONSTELLATION AND PHYSICAL LAYER RATE

| Constellation | Transmission data rate |
|---|---|
| 256 APSK | 544.32 Mbps |
| 16 APSK | 272.16 Mbps |
| 4 APSK | 136.08 Mbps |

Fig. 8. The actual object of the optical transmitter.

Fig. 9. The actual object of the optical receiver.

detected by three PDs. The separated signals are then processed through optical receivers for each single color, the block diagram of which is shown in Fig. 7. With synchronization and equalization modules, the received signal is demodulated after transimpedance amplification, automatic gain control (AGC) and analog-to-digital conversion (ADC). And finally, the video signal is recovered after LPDC decoder and ASI to UDP format conversions.

Table. I gives the important parameters of the system, and the system transmission data rates with different constellations are summarized in Table. II. It is worth noting that when the constellation mapping is 256-APSK, the system data rate is above 500 Mbps in real time, enough for multimedia transmission services.

## III. SYSTEM DEMONSTRATIONS

Both the optical transmitter and the optical receiver use the 4U 19 inch rack mount chassis in the proposed system. Figs. 8 and 9 show the actual objects of the optical transmitter and receiver, respectively.

Fig.10 shows the actual object of the light source based on RGB-LEDs. For each color, the LED light source contains five single LED chips. Convex lenses are used for each single color LED source to reach a better light-focusing performance. The irradiation angle of each LED source can be adjusted to improve the lighting quality.

The whole system is demonstrated in Fig. 11. The UHDTV programs played by three computers are modulated and sent

Fig. 10. The actual object of the light source with RGB-LEDs.

Fig. 11. Overall system demonstrations.

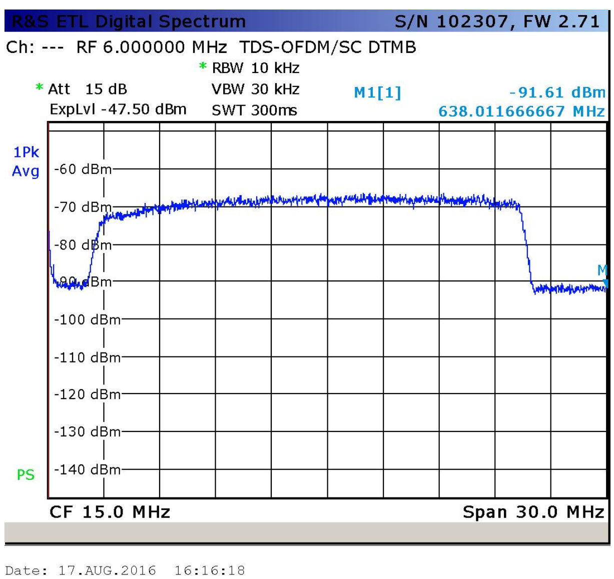


Fig. 12. Spectrum of individual color received signal.

by the optical transmitter. After passing through the optical channel, the signals are received and demodulated by the optical receiver, and the UHDTV programs are displayed on the televisions.

The distance between the light sources and the PDs is 0.5m. Three televisions finally display the transmitted video signals. The spectrum of one individual color signal is shown in Fig. 12. The system is able to transmit and receive the signals in real time, with a physical layer rate reaching 544.32 Mbps.

When the distance between the light source and the PD is getting larger or the angle of incidence is getting smaller, the physical layer rate is still more than 100 Mbps in real time with a lower order modulation, including 16-APSK and 4-APSK.

## IV. Conclusion

A real-time high-speed VLC system based on RGB-LEDs for WIMC is proposed in this paper. Including the application of TDS-OFDM, digital pre-distortion, WDM and other technologies, the system is described and demonstrated in details. The research results show that the proposed VLC system can reach a transmission data rate beyond 500 Mbps in real time, while ensuring a 100 Mbps rate under relatively bad channel conditions, which meets the wireless indoor multimedia communication requirements.

## Acknowledgment

This work was supported in part by National Basic Research Program of China (973 Program) 2012CB316000, Science Technology Project of State Grid Corporation of China (Grant No. SGHAZZ00FCJS1500238) and Natural Science Foundation of Guangdong Province of China (Grant No. 2015A030312006).

## References

[1] M. Kuipers and R. Prasad, "Pre-distorted amplifiers for OFDM in wireless indoor multimedia communications," *VTC2000-Spring. 2000 IEEE 51st Vehicular Technology Conference Proceedings*, Tokyo, 2000, pp. 395-399.

[2] H. Kim, D. Kim, S. Yang, Y. Son and S. Han, "Inter-cell interference mitigation and indoor positioning system based on carrier allocation visible light communication," *2011 5th International Conference on Signal Processing and Communication Systems (ICSPCS)*, Honolulu, HI, 2011, pp. 1-7.

[3] H. Elgala, R. Mesleh and H. Haas, "Indoor optical wireless communication: potential and state-of-the-art," in *IEEE Communications Magazine*, vol. 49, no. 9, pp. 56-62, September 2011.

[4] J. M. Kahn and J. R. Barry, "Wireless infrared communications," in *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265-298, Feb 1997.

[5] J. Armstrong, "OFDM for Optical Communications," in *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189-204, Feb.1, 2009.

[6] Y. Deng, J. Wang and Z. Chen, "Equalization without noise enhancement for dual PN padding TDS-OFDM," *2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Nara, 2016, pp. 1-3.

[7] 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," in *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1-6, June 2016.

[8] C. Ribeiro, M. Figueiredo and L. N. Alves, "A real-time platform for collaborative research on Visible Light Communication," *2015 4th International Workshop on Optical Wireless Communications (IWOW)*, Istanbul, 2015, pp. 112-116.

[9] Y. Xue, Y. Hou, S. Xiao, Y. Zhang and L. Zhang, "Real-time visible light communication system based on 2ASK-OFDM coding," *2016 21st OptoElectronics and Communications Conference (OECC) held jointly with 2016 International Conference on Photonics in Switching (PS)*, Niigata, Japan, 2016, pp. 1-3.

[10] L. Grobe et al., "High-speed visible light communication systems," in *IEEE Communications Magazine*, vol. 51, no. 12, pp. 60-66, December 2013.

[11] Z. Liu, Q. Xie, K. Peng and Z. Yang, "APSK Constellation with Gray Mapping," in *IEEE Communications Letters*, vol. 15, no. 12, pp. 1271-1273, December 2011.

[12] J. Fu, J. Wang, J. Song, C. Y. Pan and Z. X. Yang, "A Simplified Equalization Method for Dual PN-Sequence Padding TDS-OFDM Systems," in *IEEE Transactions on Broadcasting*, vol. 54, no. 4, pp. 825-830, Dec. 2008.

[13] J. A. Sills and R. Sperlich, "Adaptive power amplifier linearization by digital pre-distortion using genetic algorithms," *Proceedings RAWCON 2002. 2002 IEEE Radio and Wireless Conference (Cat. No.02EX573)*, 2002, pp. 229-232.