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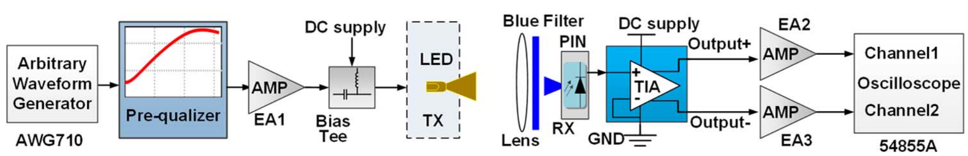

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2.0-Gb/s Visible Light Link Based on Adaptive Bit Allocation OFDM of a Single Phosphorescent White LED

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Abstract: In this paper, we present a high-speed visible light communication (VLC) system based on a single commercially available phosphorescent white light-emitting diode (LED). In this system, a preequalization circuit is used to extend the modulation bandwidth, and a differential output receiver is utilized to reduce the system noise. With adaptive bit and power allocation and orthogonal frequency-division multiplexing (OFDM), we experimentally demonstrated a 2.0-Gb/s visible light link over 1.5-m free-space transmission, and the BER is under a preforward error correction limit of 3.8×10^{-3}. To the best of our knowledge, this is the highest white-light VLC data rate using a single phosphorescent white LED.

Index Terms: Visible light communication (VLC), adaptive bit allocation, pre-equalization, orthogonal frequency-division multiplexing (OFDM), phosphorescent white light-emitting diode (LED).

1. Introduction

Light-emitting diodes (LEDs) have many advantages, such as high luminance efficiency, long life, low cost, and power consumption and security, which make them considered as the most promising device of next-generation illumination. Based on the illuminating LEDs, visible light communications (VLC) has been an area of growing interest because of the numerous advantages, including free licensed bandwidth, no electromagnetic interference, and security. The most challenged factor of achieving high speed VLC transmission is the very limited bandwidth, usually about several megahertz of the commercial LED [1], [2]. Several approaches can be utilized to extend the −3 dB modulation bandwidth of the commercial LED and to increase the data rate, such as blue light filter, pre-equalization, and post-equalization. Pre-equalization circuits can be used to increase the response of high frequency and attenuate the lower frequency. In 2008, a data rate of 80 Mb/s based on On-Off Keying-Non Return to Zero (OOK-NRZ) using multiple-resonant equalization was achieved with a phosphorescent white LED operating over a very short distance of 10 cm [1]. In 2014, Nobuhiro Fujimoto and Shohei Yamamoto performed a 662 Mb/s OOK-based transmission with pre- and post-equalized circuits and a blue chip of a RGB LED at the distance of 15 cm [4]. In 2014, based on analog pre-emphasis circuit and post-equalization circuit, a 550 Mb/s NRZ-OOK VLC transmission was realized by a commercial phosphorescent white light LED at the distance of 60 cm [5]. The most effective way is to developing faster LEDs, like resonant-cavity LEDs (RC-LEDs) that can have –3 dB bandwidth of about 70 MHz [6] and uLEDs at least 60 MHz [7]–[9]. Based on the RC-LED, a data rate of 300 Mb/s was achieved using OOK over 11 m transmission [6]. A speed of up to 1 Gb/s was demonstrated for μLED with OOK modulation [8].

Spectrally efficient modulation techniques such as OFDM or discrete multitone (DMT), single carrier frequency domain equalization (SC-FDE) and carrier-less amplitude and phase (CAP) modulation, can be utilized to greatly increase the data rate. Combining high order Quadrature amplitude modulation (QAM) and wavelength division multiplexing (WDM), the data rates of 575 Mb/s [10] and 2.5 Gb/s [11] with OFDM, 3.4 Gb/s [2] and 5.6 Gb/s (RGBA LED) [12] with DMT, 4.22 Gb/s with SC-FDE [13], and 4.5 Gb/s with CAP [14] have been obtained. Because of the lower complexity and lower cost, the phosphorescent white LEDs are more attractive for general illumination when compared with the RGB type LEDs. In references [15] and [16], a data rate of 190 has been obtained at the free space transmission lengths of 0.75 m with equalization circuit and without blue filter, and 185 Mbps without equalization circuit and blue filter under a transmission distance of 0.8 m using phosphorescent white LED. 225-Mb/s data rate is reported using a commercially available phosphorescent white LED [10]. In [17], using adaptive bit and power loading DMT modulation, a data rate of 1 Gb/s VLC link has been realized using a phosphorescent white LED at a distance of 10 cm. The data rate of 1.68 Gb/s at a distance of 3 cm has been demonstrated using white light generated by a blue GaN μLED and a yellow fluorescent copolymer [9]. This is a special designed micro-structure LED, which supposed to have a much wider bandwidth than the commercial LEDs.

In our previous work, we proposed a bridged-T amplitude equalizer circuit for VLC system using red LED and APD receiver. The data rate is 750 Mb/s with 64QAM-OFDM [18] and improved to 1.42 Gb/s by bit and power allocation OFDM [19], and the date rates can be increased by the pre-equalizer. Compared with the red LED, the data rate will be lower when using phosphorescent white LED because of the slow-responding phosphorescent component, under the same experimental conditions with only different LED transmitters. In [20], we realized 1.6 Gb/s VLC transmission by 16QAM-OFDM based on a commercially available phosphorescent white LED at a distance of 1 m, and shown that the cascaded pre-equalizer has a great improvement on increasing the –3 dB bandwidth and the differential output receiver can be utilized to improve the transmission data rate. In the record-breaking VLC experiments [2], [9], [12], [17], adaptive bit and power allocation has been employed since it can make full use of the limited modulation bandwidth based on the characteristic of VLC channel.

In this paper, we report a high speed VLC system based on a single commercially available phosphorescent white LED. In this VLC system, a pre-equalization circuit is used to extend the modulation bandwidth and a low-cost differential outputs PIN receiver is utilized to reduce the system noise. Using adaptive bit and power allocation OFDM, we successfully demonstrated a 2.0-Gb/s VLC link over 1.5 m free space transmission and 0.79-Gb/s data rate over 3.0 m, with the BER results under pre-FEC limit of 3.8×10^{-3}. Compared with the work we done in [18] and [19], we use phosphorescent white LED and wider bandwidth PIN receiver to replace red chip of RGB LED and APD receiver, respectively. Utilizing adaptive bit and power allocation OFDM, and the date rate have greatly improved and transmission distance also increased when compared with the work we done in [20]. To the best of our knowledge, this is the highest white light VLC data rate ever reported using a single phosphorescent white LED.

2. Principle of Amplitude Equalizer for VLC System

In Fig. 1, we present the schematic of the amplitude equalizer used in VLC system. The detailed principle of the amplitude equalizer is shown in [19]. Z_{11} is the equivalent impedance of resistor R_1, capacitor C_1, and inductor L_1, and Z_{22} is the equivalent impedance of resistor R_4, capacitor

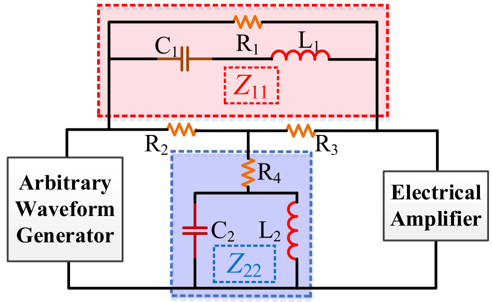

Fig. 1. Schematic of the amplitude equalizer.

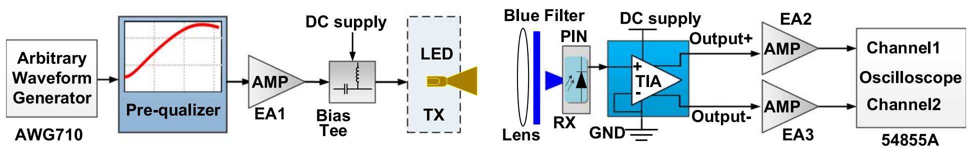

Fig. 2. Experimental setup of VLC system.

C_2, and inductor L_2. R_2 and R_3 are both equal to R_L. The frequency response H_{eq} of the equalizer can be expressed as

$$H_{eq} = \frac{1}{2\left(1 + \frac{R_L}{R_4 + j\omega L_1/(1-\omega^2 C_1 L_1)}\right)} \quad (1)$$

when the output impedance of the arbitrary waveform generator (AWG) Z_S and the impedance of the electrical amplifier (EA) Z_L are both equal to R_L, and $L_1 = L_2$, $C_1 = C_2$. The relation between resistors R_1 and R_4 is $R_1{}^* R_4 = R_L{}^2$. The parameter ω is the angular frequency and equal to $2\pi^* f$, where f is frequency.

In (1), when $1 - \omega^2 C_1 L_1$ tends to zero, the maximum limitation of H_{eq} is 0.5. H_{eq} gets the maximal value when $f = 1/2\pi\sqrt{C_1 L_1}$; when ω tends to zero and R_L is constant, $H_{eq} = 1/2(1 + R_L/R_4)$, and the lower frequency response is decided by R_1 or R_4.

3. Experimental Details

3.1. Experimental Setup

The experimental setup of VLC data transmission system using the pre-equalizer is shown in Fig. 2. In this scheme, the original driving signal is from AWG (Tektronix AWG710) and pre-equalized by the amplitude equalizer. After amplified by EA1 (Minicircuits, gain: typical 25 dB, minimum output power at 1 dB compression: 22 dBm, and –3 dB bandwidth: 500 MHz), the amplified signal is combined with direct current (DC) using bias Tee and applied to a single commercially available phosphorescent white LED (OSRAM, LCWCRDP.EC) acting as the optical transmitter. In order to focus a high proportion of light onto the PIN receiver, a lens (diameter: 55 mm, focus length: 18 mm) is placed before the receiver. The blue filter is placed in front of the PIN photodiode to filter out the slow-responding phosphor component. The blue filter has very high transmittance average 97.5% from 430 nm to 485 nm in the blue signal range and very wide stop-band from 500 to 1050 nm [21]. A low-cost commercial PIN photodiode (HAMAMATSU S10784, effective photosensitive area: 7 mm^2, and 0.45 A/W sensitivity with –3 dB bandwidth of 300 MHz at 660 nm) is used to convert optical signal to electrical signal. Then, the electrical signal is amplified by a differential outputs trans-impedance amplifier (TIA) designed with MAX3665 (gain of 8 KΩ and –3 dB bandwidth of 470 MHz). The differential

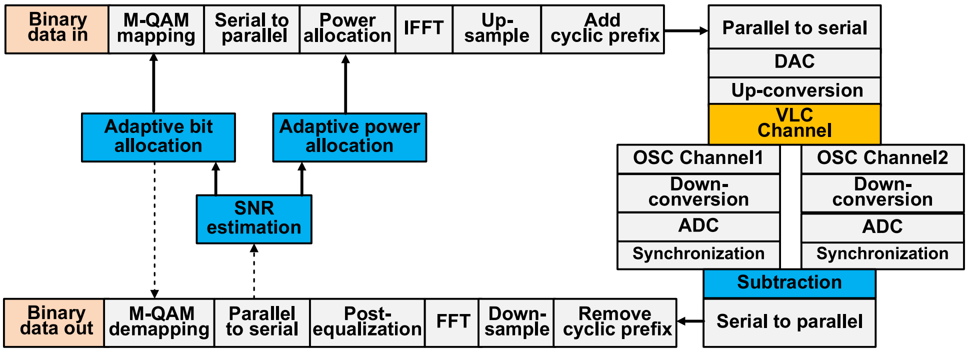

Fig. 3. Block diagram of implementing bit and power allocation with OFDM.

outputs of TIA are respectively amplified by EA2 and EA3 (Minicircuits, gain: typical 25 dB, minimum output power at 1 dB compression: 22 dBm, and –3 dB bandwidth: 500 MHz). The output signals of EA2 and EA3 are recorded simultaneously by channel1 and channel2 by a real-time digital oscilloscope (OSC, Agilent 54855 A).

3.2. Implementation of Bit and Power Allocation With OFDM

The diagram of implementing bit and power allocation with OFDM is shown in Fig. 3. In the implementation, the OFDM transmitter consists of M-ary QAM (M-QAM, 1 for BPSK, 2 for QPSK, 3 for 8-QAM, 4 for 16-QAM etc.) modulation based on adaptive bit allocation, serial-to-parallel conversion, power allocation based on adaptive power allocation, inverse fast Fourier transform (IFFT), up-sample, adding cyclic prefix (CP), parallel-to-serial conversion, digital-to-analog converter (DAC) and up-conversion. DAC is used to transform the time-domain digital data to time-domain analog data. Up-conversion is performed to up-convert the signal to the transmission frequency. The OFDM signal is loaded to an AWG as the input of the VLC system and goes through the VLC channel. At the receiver, the final differential output signals are captured by channel1 and channel2 of OSC. An offline digital signal processing program by Matlab is used to demodulate the OFDM signal. First, differential signal channel1 subtracts channel2 after synchronizations. Then, the resulted signal is demodulated by the following steps, including removing CP, serial-to-parallel conversion, down-sample, fast Fourier transform (FFT), post-equalization, and M-QAM decoding. The post-equalization method is zero-forcing equalization by a training sequence. The M-QAM decoding need the bit allocation information of every subcarrier. Finally, we calculate the BER by comparing the original binary data and recovered binary data. Other detailed parameters of the generated OFDM signals include: subcarrier number = 256, up-sampling factor = 3. The data rate includes the 3.03% CP, 2% training sequence, and 7% forward error correction (FEC) overhead.

Before applying bit and power allocation, the signal-to-noise ratio (SNR) of the VLC channel is estimated through error vector magnitude (EVM) method using BPSK-OFDM [22]. The total data rate can be calculated as

$$R = \frac{B\left(\sum_{k=1}^{N} \log_2 M_k\right)}{N} \tag{2}$$

where B is the modulation bandwidth of the system, N is the total subcarrier number, and M_k is the constellation size of the kth subcarrier.

4. Results and Discussions

To maximize the transmission data rate of the VLC system, we have designed several different kinds with different parameters, including single and cascaded pre-equalizers. We find the

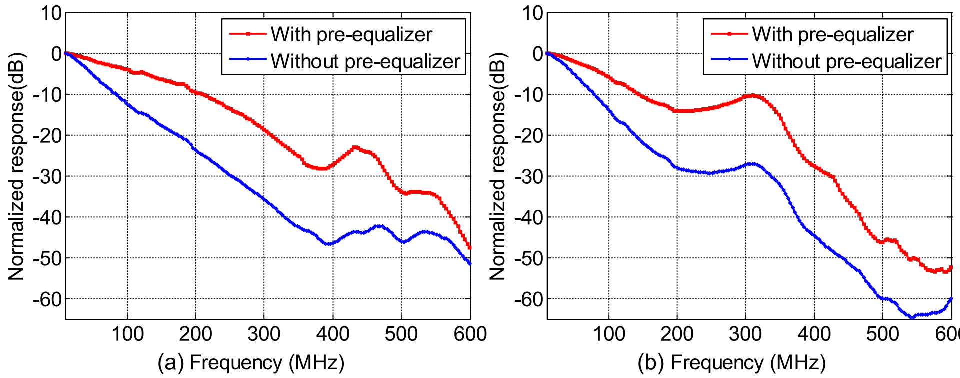

Fig. 4. Measured forward transmission gains (a) channel1 and (b) channel2.

most suitable pre-equalizer using for the bit and power allocation OFDM. The parameters of the best pre-equalizer used in this paper are $R_1 = 499\ \Omega$, $R_2 = R_3 = 49.9\ \Omega$, $R_4 = 5\ \Omega$, $C_1 = C_2 = 8.5$ pF, and $L_1 = L_2 = 22$ nH. The forward transmission gains of the differential outputs are measured by the vector network analyzer (VNA, Agilent, N5230C) operating from 10 MHz to 40 GHz, and the output power of VNA is fixed at −25 dBm, which is relatively small to avoid saturation distortion. The distance between the transmitter LED and receiver PIN is 150 cm. In Fig. 4, using the blue filter, we show the measured forward transmission gains of the differential outputs with pre-equalizer and without pre-equalizer in VLC system. Using blue filter, the −3 dB bandwidths of channel1 and channel2 are both 28 MHz (from 10 MHz to 38 MHz) and, respectively, improved to 66 MHz (from 10 MHz to 76 MHz) and 55 MHz (from 10 MHz to 55 MHz) using the pre-equalizer. With lower frequencies attenuated by using the passive equalizer, the transmit power with equalizer is larger than that without the equalizer to achieve the best working condition [19].

In the data transmission experiments, the distance is 150 cm between the transmitter LED and receiver PIN. The sampling rates of the AWG and OSC are fixed at 1.8 G Sample/s and 2 G Sample/s, respectively. The modulation bandwidth is 600 MHz from DC to 600 MHz. SNR estimation is performed using BPSK-OFDM and all the individual subcarrier has equal power. After exhaustive experiments by varying the signal driving peak-to-peak voltage V_{pp} of AWG and bias current Ibias of the phosphorescent white LED, we obtain the optimal biasing point to be $V_{pp} = 1.2$ V and $I_{\text{bias}} = 426$ mA. The illuminance is about 651 lx measured before the lens at the distance of 150 cm using the light meter (FLUKE, 941, Light Illuminance Meter Tester). The bit and power allocation scheme utilized in this paper is based on the work of [23].

In Fig. 5(a), we show the estimated SNR of VLC channel versus subcarrier index. Based on the estimated SNR, the adaptive bit allocation algorithm can adaptively allocate the modulation order (bits/symbol) to different subcarriers, that is, modulation order higher with the better SNR, so the bandwidth can be fully employed and the total data rate will be improved. Fixing the transmission data rate at 2.28 Gb/s (average bit per subcarrier: 3.8 bits/symbol), the bit and power allocation of different subcarriers are presented in Fig. 5(b) and (c), respectively. In Fig. 5(b), 46 subcarriers are omitted because of the lower SNR and the frequency of the last subcarrier is 520.8 MHz. The assigned maximum modulation order is 6 bits/symbol (64 QAM) and the minimal is 2 bits/symbol (QPSK). The power allocation is illustrated in Fig. 5(c) and the modulation orders have been considered when implementing the power loading algorithm. In Fig. 6, we present the BER result as a function of the subcarrier index. It can be found that some subcarriers have higher BER since the channel has changed slightly at different time. The average BER of all subcarriers (excluding the subcarriers without allocating bits) is 2.17×10^{-3} and under the pre-FEC limit of 3.8×10^{-3}. Consider the 3.0% CP, 2% training sequence, and 7% forward error correction (FEC) overhead; the data rate is 2.0 Gb/s at 150 cm. The constellations of different modulation orders are also shown in Fig. 6.

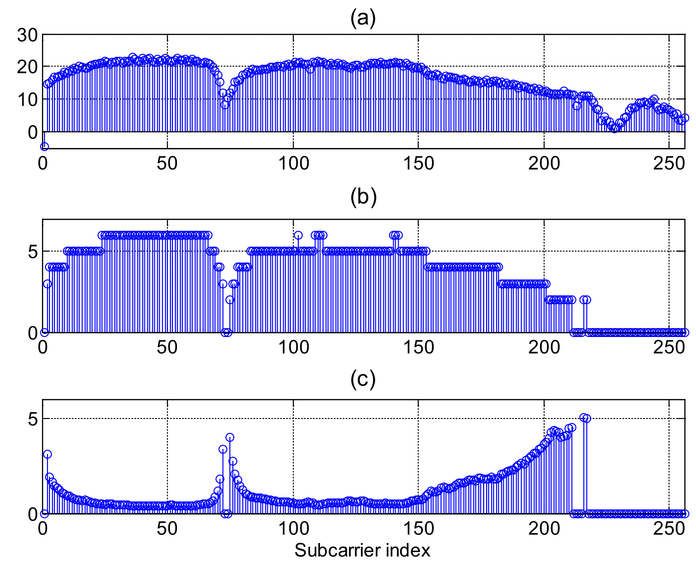

Fig. 5. (a) SNR estimation. (b) Bit and (c) power allocation scheme of 2.28 Gb/s at 150 cm.

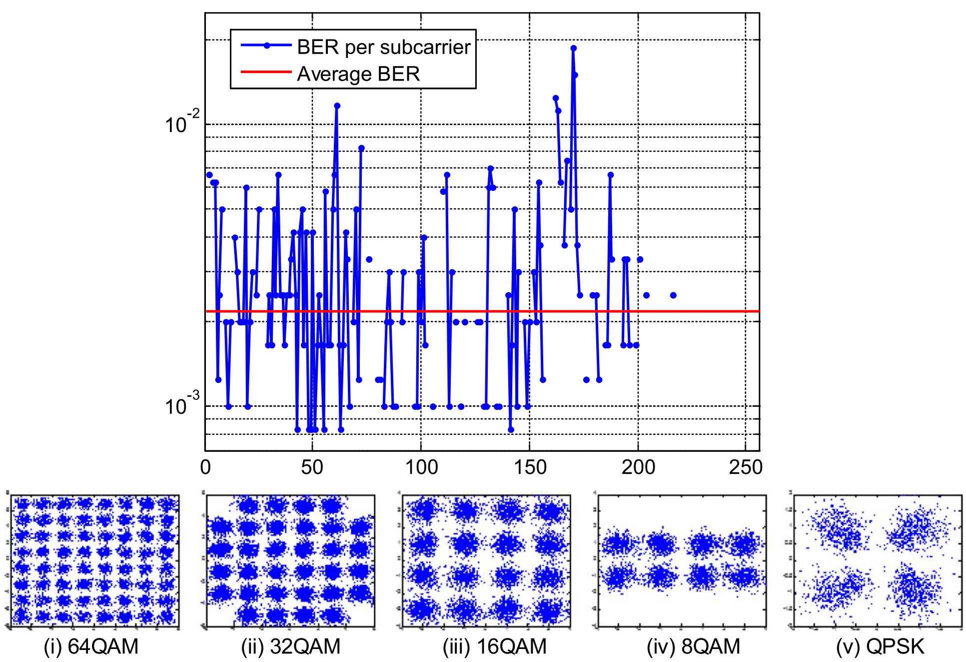

Fig. 6. Measured BER results on individual subcarriers and the constellations of 2.28 Gb/s at 150 cm.

In Fig. 7, we show BER results as a function of the data rate with the distance from 150 cm to 300 cm. The illumination levels range (approximately) from 651 lx (150 cm) to 134 lx (300 cm). The BER results increase with higher data rate and longer transmission distance. When the transmission distance becomes longer, the received optical power at receiver will decrease and the SNR of the VLC system deteriorates, and therefore, the data rate should be reduced to meet the requirement of the pre-FEC limit. The total data rates are respectively 2.28-Gb/s, 1.74-Gb/s, 1.50-Gb/s, and 0.90-Gb/s over the distance of 150 cm, 200 cm, 250 cm, and 300 cm, and considering the overhead, the data rates will be 2.00-Gb/s, 1.53-Gb/s, 1.32-Gb/s, and 0.79-Gb/s. To date, it is the highest data rate ever achieved by employing a single commercially available phosphor-based white LED in VLC systems reported.

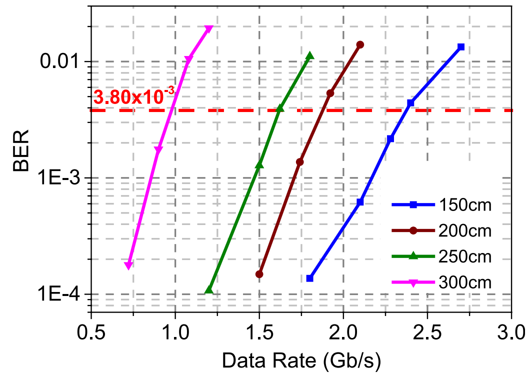

Fig. 7. BERs at different data rates and distances.

5. Conclusion

In this paper, we demonstrate a very-high-speed VLC system based on a single commercially available phosphorescent white LED. In this VLC system, a pre-equalization circuit is used to extend the modulation bandwidth, and a low-cost differential outputs PIN receiver is utilized to reduce the system noise and increase data rate. Combining OFDM and adaptive bit and power allocation algorithm, we successfully realize a 2.0-Gb/s VLC link over 1.5 m free space transmission and 0.79-Gb/s data rate over 3.0 m, with the BER results under pre-FEC limit of 3.8×10^{-3}. This demonstration is conducted at a practical distance. To the best of our knowledge, this is the fastest white light VLC data rate transmission using a single phosphorescent white LED ever achieved.

References

[1] H. L. Minh *et al.*, “High-speed visible light communications using multiple-resonant equalization,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 14, pp. 1243–1245, Jul. 2008.
[2] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, “3.4 Gbit/s visible optical wireless transmission based on RGB LED,” *Opt. Exp.*, vol. 20, no. 26, pp. B501–B506, Dec. 2012.
[3] H. L. Minh *et al.*, “80 Mb/s visible light communications using pre-equalized white LED,” in *Proc. 34th ECOC*, Sep. 21–25, 2008, pp. 352–353.
[4] N. Fujimoto and S. Yamamoto, “The fastest visible light transmissions of 662 Mb/s by a blue LED, 600 Mb/s by a red LED, and 520 Mb/s by a green LED based on simple OOK-NRZ modulation of a commercially available RGB-type white LED using pre-emphasis and post-equalizing techniques,” in *Proc. 40th ECOC*, Sep. 21–25, 2014, pp. 1–3.
[5] H. Li, X. Chen, J. Guo, and H. Chen, “A 550 Mb/s real-time visible light communication system based on phosphorescent white light LED for practical high-speed low-complexity application,” *Opt. Exp.*, vol. 22, no. 22, pp. 27203–27213, Nov. 2014.
[6] P. H. Binh *et al.*, “Demonstration of 300 Mb/s free space optical link with commercial visible LED,” in *Proc. IEEE 11th Int. NEWCAS Conf.*, 2013, pp. 1–3.
[7] D. Tsonev *et al.*, “A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 7, pp. 637–640, Apr. 2014.
[8] J. J. McKendry *et al.*, “High-speed visible light communications using individual pixels in a micro light-emitting diode array,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 18, pp. 1346–1348, Sep. 2010.
[9] H. Chun *et al.*, “Visible light communication using a blue GaN μLED and fluorescent polymer color converter,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 20, pp. 2035–2038, Oct. 2014.
[10] Y. Wang, Y. Wang, N. Chi, J. Yu, and H. Shang, “Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED,” *Opt. Exp.*, vol. 21, no. 1, pp. 1203–1208, Jan. 2013.
[11] N. Chi, Y. Wang, Y. Wang, X. Huang, and X. Lu, “Ultra-high-speed single red-green-blue light-emitting diode-based visible light communication system utilizing advanced modulation formats,” *Chin. Opt. Lett.*, vol. 12, no. 1, Jan. 2014, Art. ID. 010605.
[12] G. Cossu, A. Wajahat, R. Corsini, and E. Ciaramella, “5.6 Gb/s downlink and 1.5 Gb/s uplink optical wireless transmission at indoor distance (1.5 m),” in *Proc. 40th ECOC*, Sep. 21–25, 2014, pp. 1–3.
[13] Y. Wang, X. Huang, J. Zhang, Y. Wang, and N. Chi, “Enhanced performance of visible light communication employing 512 QAM N-SC-FDE and DD-LMS,” *Opt. Exp.*, vol. 22, no. 13, pp. 15328–15334, Jun. 2014.

[14] Y. Wang, X. Huang, L. Tao, J. Shi, and N. Chi, “4.5-Gb/s RGB-LED based WDM visible light communication system employing CAP modulation and RLS based adaptive equalization,” *Opt. Exp.*, vol. 23, no. 10, pp. 13626–13633, May 2015.
[15] C. H. Yeh, C. W. Chow, H. Y. Chen, J. Chen, and Y. L. Liu, “Adaptive 84.44-190 Mbit/s phosphor-LED wireless communication utilizing no blue filter at practical transmission distance,” *Opt. Exp.*, vol. 22, no. 8, pp. 9783–9788, Apr. 2014.
[16] C. H. Yeh *et al.*, “Investigation of no analogue-equalization and blue filter for 185 Mbps phosphor-LED wireless communication,” *Opt. Quantum Electron.*, vol. 47, no. 7, pp. 1991–1997, Jul. 2015.
[17] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, “1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation,” *IEEE Photon. J.*, vol. 4, no. 5, pp. 1465–1473, Oct. 2012.
[18] X. Huang *et al.*, “750 Mb/s visible light communications employing 64QAM-OFDM based on amplitude equalization circuit,” in *Proc. OFC Conf. Exhib.*, Mar. 22–26, 2015, pp. 1–3.
[19] X. Huang, J. Shi, J. Li, Y. Wang, and N. Chi, “A Gbps VLC transmission using hardware pre-equalization circuit,” *IEEE Photon. Technol. Lett.*, vol. 27, no. 18, pp. 1915–1918, Sep. 2015.
[20] X. Huang, Z. Wang, J. Shi, Y. Wang, and N. Chi, “1.6 Gbit/s phosphorescent white LED based VLC transmission using a cascaded pre-equalization circuit and a differential outputs PIN receiver,” *Opt. Exp.*, vol. 23, no. 17, pp. 22034–22042, Aug. 2015.
[21] S. W. Wang *et al.*, “A high-performance blue filter for a white-led-based visible light communication system,” *IEEE Wireless Commun.*, vol. 22, no. 2, pp. 61–67, Apr. 2015.
[22] R. A. Shafik, M. S. Rahman, and A. H. M. Islam, “On the extended relationships among EVM, BER and SNR as performance metrics,” in *Proc. ICECE*, 2006, pp. 408–411.
[23] R. F. Fischer and J. B. Huber, “A new loading algorithm for discrete multitone transmission,” in *Proc. GLOBECOM, Key Global Prosperity*, 1996, vol. 1, pp. 724–728.