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# Phosphor-LED-Based Wireless Visible Light Communication (VLC) and Its Applications

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Additional information is available at the end of the chapter

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## Abstract

In this chapter, we review our recent works on the phosphor white-light light-emitting diode (LED)-based wireless visible light communication (VLC) and its applications. This chapter is divided into two sections for introduction. In the first section, in order to enhance the transmission rate in phosphor-LED VLC system, we propose and demonstrate a novel multiband orthogonal-frequency-division-multiplexed (OFDM) modulation format for capacity enhancement. Based on the proposed scheme, various bands of OFDM signals are employed to different LED chips of the LED luminary; it can prevent the power fading and nonlinearity effects of transmission signal. Therefore, the maximum enhanced percentage of VLC data rate is 41.1%. In the second section, we also demonstrate a 71.3–148.4 Mbps phosphor-LED wireless VLC system at the free space transmission distance between 1.4 and 2.1 m. Finally, to understand and demonstrate the real-time LED VLC transmission, a commercial OFDM-based digital signal processor (DSP) is used in the LED transmitting side and client side, respectively. Therefore, the proposed real-time half-duplex VLC system can complete around 70 Mbps downstream and upstream traffic throughputs, in a free space transmission distance of 2 m long for practical in-home illumination and smart city applications.

**Keywords:** phosphor LED, visible light communication (VLC), Li-Fi, OFDM modulation, Internet of thing (IoT), smart city

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## 1. Introduction

Recently, because of the benefits of low power consumption, high-efficiency, and long lifetime for light-emitting diodes (LEDs), the traditional incandescent and fluorescent lamps are inherited by the LEDs [1–5]. Furthermore, the LEDs have a broad modulation bandwidth comparing to these conventional lighting components [6–8]. Hence, utilizing

the LED devices to combine illumination and wireless visible light communication (VLC) system has interested many advertences for the future lighting and network access markets [9–12]. Due to the LED-based VLC system without electromagnetic interference (EMI) effect, it also can be employed in wireless communication inhibited areas, such as hospital or aircraft [13–14]. Besides, compared with the red-green-blue (RGB) white-light LED, the white-light phosphor-LED is naturally used for the wireless VLC transmission [15, 16]. However, the long relaxation time of yellow phosphor nature will narrow the modulation bandwidth of white-light LED in a few MHz and reduce the VLC capacity for end-user [1, 17].

In order to increase and extend the modulation bandwidth of phosphor-LED, utilizing a blue optical filter in client side to remove the slow response produced by phosphor [18], employing spectral-efficient advanced discrete multitone (DMT) or orthogonal-frequency-division-multiplexed quadrature-amplitude-modulation (OFDM-QAM) modulations [19, 20], applying multi-input multi-output (MIMO) algorithm in VLC [21], and exploiting analogy equalization and filtering circuits in transmitter (Tx) and receiver (Rx) sides [22] have been proposed and demonstrated, respectively. In addition, utilizing advanced OFDM modulation signal for high data rate VLC transmission has also been demonstrated by Prof. Haas's group. They proposed using asymmetrically clipped optical (ACO) OFDM and DC-biased optical (DCO) OFDM for the indoor LED VLC network system to reducing LED clipping distortions [23, 24]. While the RGB-based white-light LED was employed in the VLC transmission, 110 Mbps OFDM traffic rate was also reached [25].

If the key function of the LED luminary is applied for lighting, it will confront the communication characteristics of optical wireless VLC [26]. Hence, how to use the commercially available white-light LED luminary to optimize both the illumination and communication is important and desirable issue for practical in-home illumination application [6, 13].

In this chapter, we will introduce our recent works on the white-light phosphor-LED-based wireless VLC system and its applications. This chapter will be divided into two sections for introduction. In the first section, to enhance the data rate in phosphor-LED VLC system, we propose and demonstrate an advanced multiband OFDM modulation design for VLC capacity enhancement. According to the proposed VLC scheme, various bands of OFDM signals are applied on different LED chips of the LED luminary; the special modulation design can prevent the power fading and nonlinearity effects of transmission signal by utilizing the same OFDM signal to the entire LED chips. As a result, the maximum enhanced percentage of VLC data rate is 41.1%, when we use the proposed novel new multiband OFDM modulation.

In the second section, we will demonstrate a 71.3–148.4 Mbps phosphor-LED wireless VLC system at the free space transmission distances between 1.4 and 2.1 m. Moreover, a commercial phosphor LED luminary with five phosphor-LED chips in series is applied for illumination and communication simultaneously. In the measurement, optical OFDM modulation signal with bit-loading algorithm is applied for proposed VLC transmission. We also investigate an optimal bias-tee circuit with equalization and filtering method to extend the modulation bandwidth from 1 to 27 MHz. Finally, to understand and demonstrate the real-time LED VLC

transmission, a commercial OFDM-based digital signal processor (DSP) is used in the LED Tx side and client Rx side, respectively. Therefore, the proposed real-time half-duplex VLC system can complete the around 70 Mbps downstream and upstream traffic throughputs, in a free space transmission distance of 2 m long. We believe that it can be a cost-effective and promising candidate for practical in-home illumination and smart city applications.

## 2. Multiband OFDM in phosphor-LED VLC system

In the first section, we will present demonstrating a multiband OFDM modulation format in phosphor-LED VLC system for data rate enhancement [27]. First of all, **Figure 1(a)** and **(b)** presents the proposed optical setup of phosphor-LED VLC transmission by utilizing single-band and triple-band OFDM modulation formats. In this experiment, we use a phosphor-LED luminary with six LED light chips for serving as the VLC transmitter (Tx). Besides, the lenses can be applied in front of the phosphor-LED-based Tx and the receiver (Rx) of client side to focus and enhance the VLC light performance simultaneously. Here, the modulated OFDM signal can be directly applied on the LED luminary via a bias-tee (BT) without analogy equalization for VLC transmission. Furthermore, the proposed BT circuit without pre-equalization function has also been demonstrated in Ref. [10]. Conventionally, the entire OFDM signal would be applied on the six LED chip in Tx-side for VLC transmission, as seen in **Figure 1(a)**. However, due to the power fading and nonlinear effect of LED, the relative electrical power spectrum drops quickly in the higher frequency range. These influences will limit the traffic rate of VLC. To overcome this issue, we propose a multiband OFDM modulation format to increase the total VLC rate. As shown in **Figure 1(b)**, the real architecture of three-band OFDM VLC transmission is investigated. Hence, the total OFDM data rate in VLC system can be divided in three data ranges ( $Data_1$ ,  $Data_2$ , and  $Data_3$ ) within a total frequency bandwidth. Each modulation bandwidth ( $Data_1$ ,  $Data_2$ , and  $Data_3$ ) has the same range for data transmission. In the measurement, the phosphor-LED luminary has six lighting chips. The triple-band OFDM signals are employed on the LED luminary directly and divided into three groups of phosphor-LED chip via three BTs for direct OFDM modulation. Hence, each group has two phosphor-LED chips. And each LED chip is driven at 3 V.

Due to the power fading and nonlinear effects, the relative electrical power spectrum drops quickly in the higher frequency range, as shown in **Figure 2(a)**, when single-band OFDM modulation is used. It would also produce poor signal-to-noise ratio (SNR) of each OFDM subcarrier for VLC transmission. Hence, the VLC rate could also be restricted under the available frequency bandwidth. To solve the issues, using triple-band OFDM would be choice for phosphor-LED VLC system. The relative electrical power spectra of triple-band OFDM signals ( $Band_1$ ,  $Band_2$ , and  $Band_3$ ) are depicted conceptually in **Figure 2(b)**. If the OFDM signal has a high peak-to-average power ratio (PAPR) by separating the OFDM into triple-band OFDM, various OFDM bands are utilized to various groups of LED chips. Therefore, much higher driving power can be employed to each LED group for enhancement. The obtained SNR of each OFDM subcarrier would enhance in each OFDM-band obviously. As a result, the total VLC rate could be improved by using proposed triple-band OFDM modulation scheme.

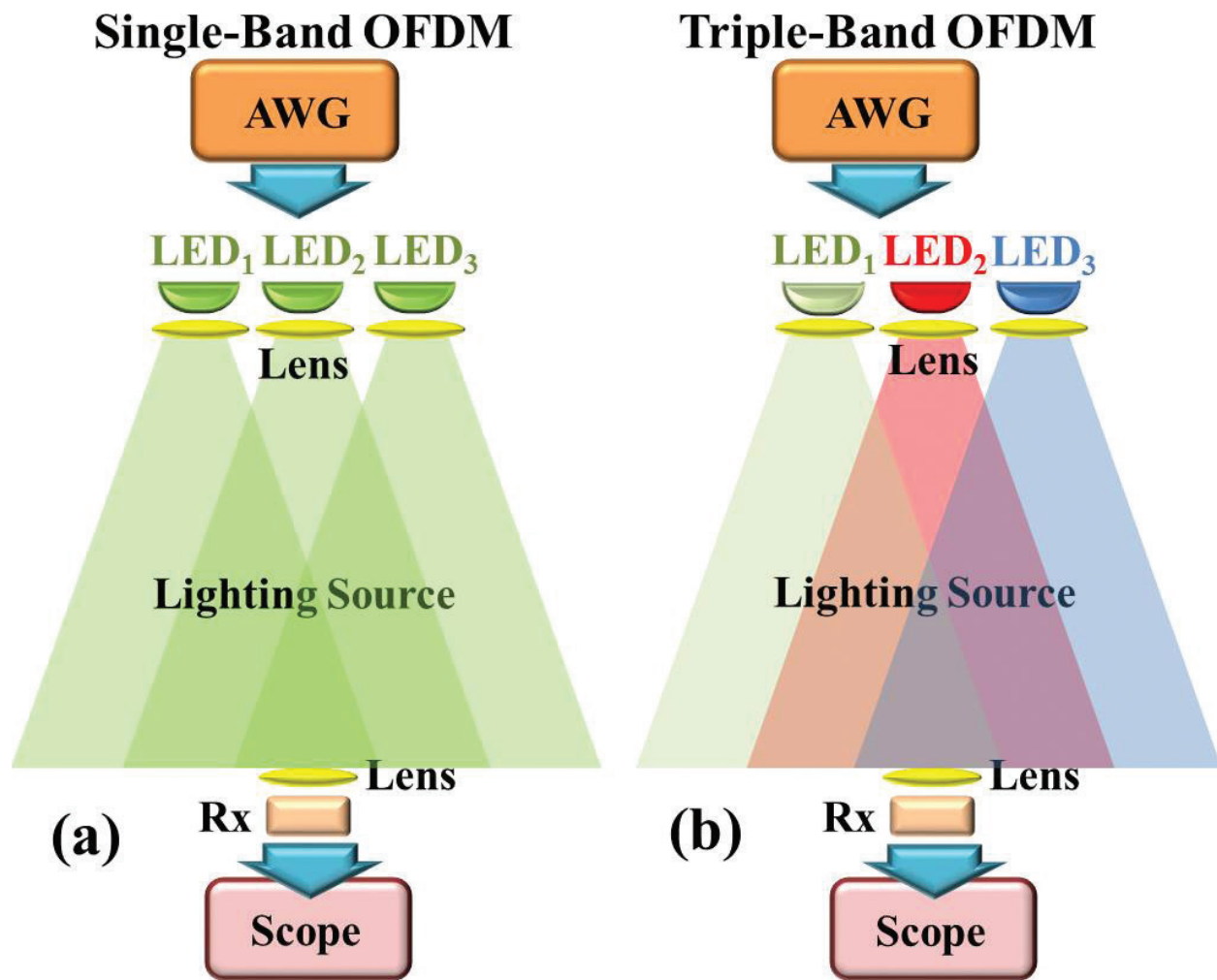


Figure 1. Proposed phosphor-LED VLC architectures using (a) single-band and (b) triple-band OFDM modulations.

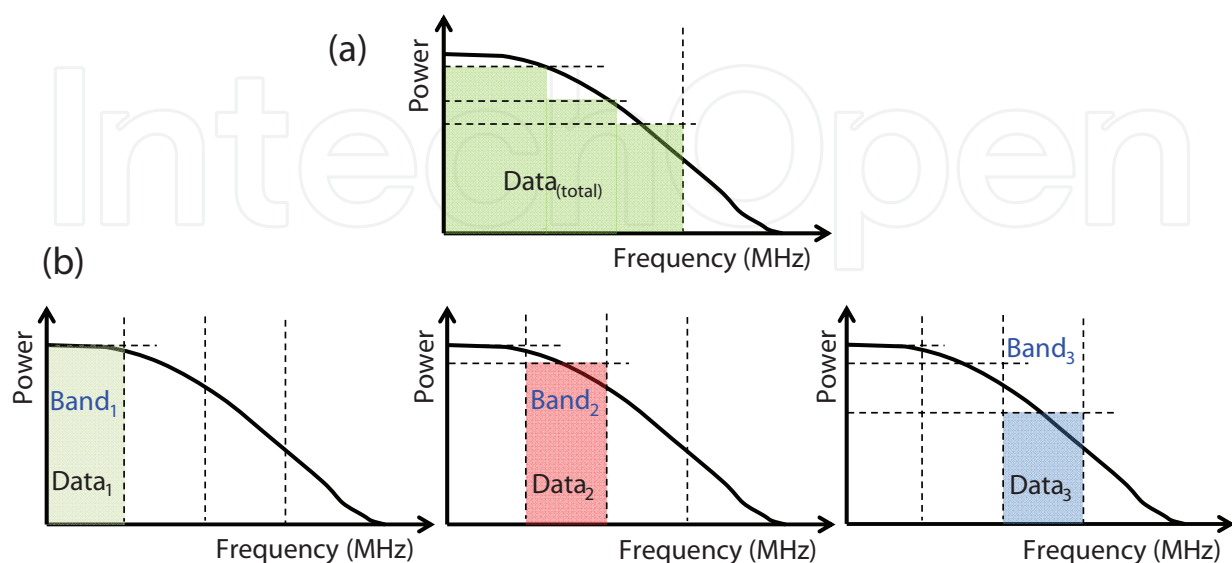
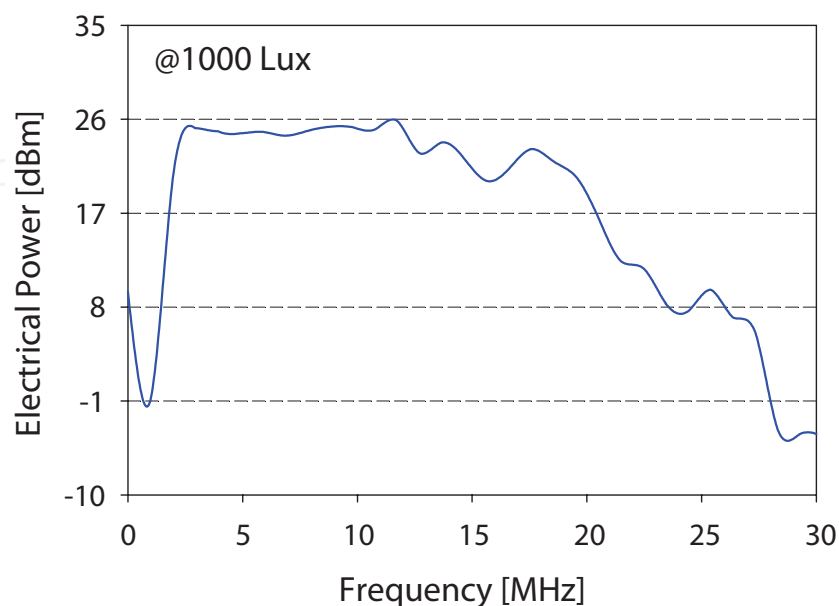


Figure 2. The relative electrical spectra under (a) single-band and (b) triple-band OFDM modulation format.



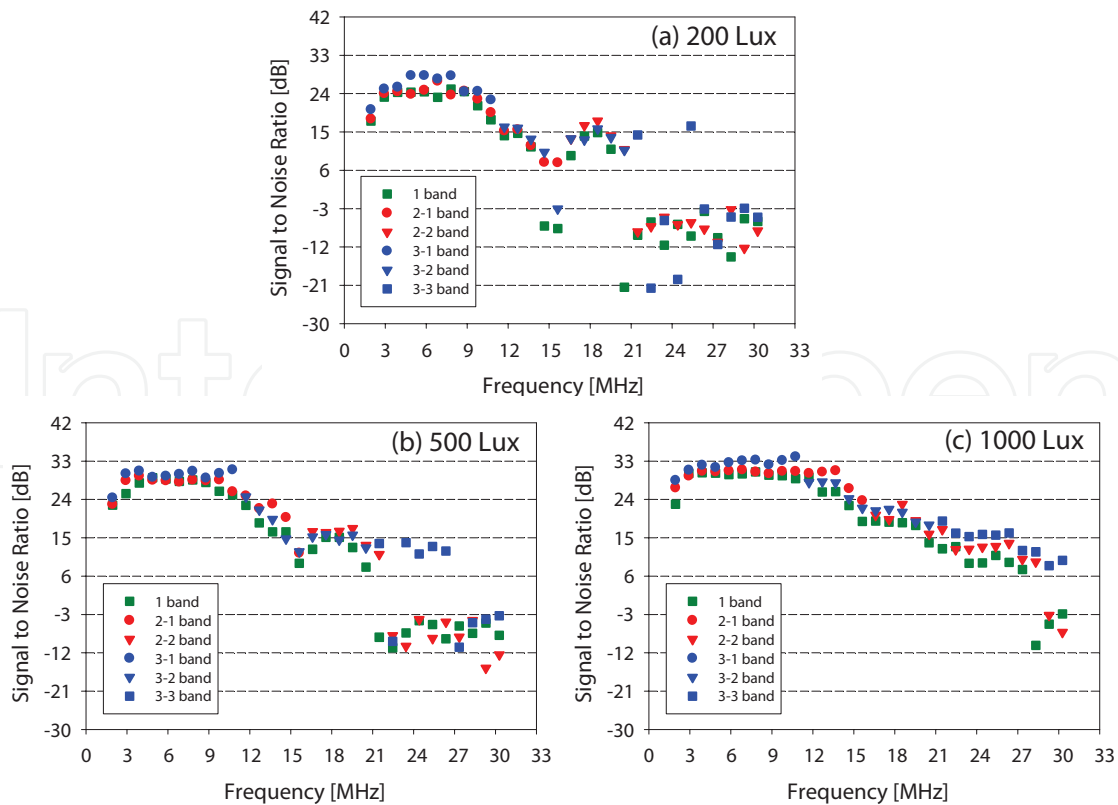
We utilize six white-light phosphor-LED chips with series connection in the experiment. Thus, the used LED luminary is driven around  $\sim 18$  V. We utilize an arbitrary waveform generator (AWG) to produce OFDM-QAM signal applying on LED luminary for VLC transmission. As shown in **Figure 1(a)**, the white-light VLC emits from the LED luminary and is detected by a silicon-based PIN Rx. Here, the detection wavelength ranges and active area of detected PIN Rx are between 350 and 1100 nm with responsivity of 0.63 A/W 150 mm<sup>2</sup>, respectively. Besides, the operated bandwidth and the root mean square (rms) noise of Rx are 50 MHz of 530  $\mu$ V, respectively. Then, the VLC wireless signal will be directly detected by a PIN Rx. Next, the detected VLC signal is amplified by a broadband electrical amplifier, and is linked by a real-time oscilloscope for signal demodulation. Finally, the corresponding bit error rate (BER) will be calculated and obtained based on the observed SNR of each OFDM subcarrier. In addition, in order to prevent the power fading and nonlinearity problems of the LED, the multi-band OFDM modulation method is first proposed in VLC system to improve the traffic rate, as seen in **Figure 2(a)**.

Normally, the phosphor-LED only reaches a few MHz modulation bandwidth without any related improvements [1, 12]. To extend the frequency bandwidth of LED, the proposed BT circuit only needs to adjust the resistance (R), inductance (L), and capacitance (C) suitably for matching the impedance of LED. Hence, we measure the modulation bandwidth of proposed VLC system, while the BT circuit is utilized. **Figure 3** displays the frequency response of phosphor-LED, while the detected illumination at Rx side is at 1000 lx. The available modulation bandwidth of 25 MHz can be reached as shown in **Figure 3**. According to the proposed BT in LED Tx side, the frequency bandwidth can be widened from a few MHz to 25 MHz. As a result, the modulation capacity of VLC system should be increased via proposed multiband OFDM signal.



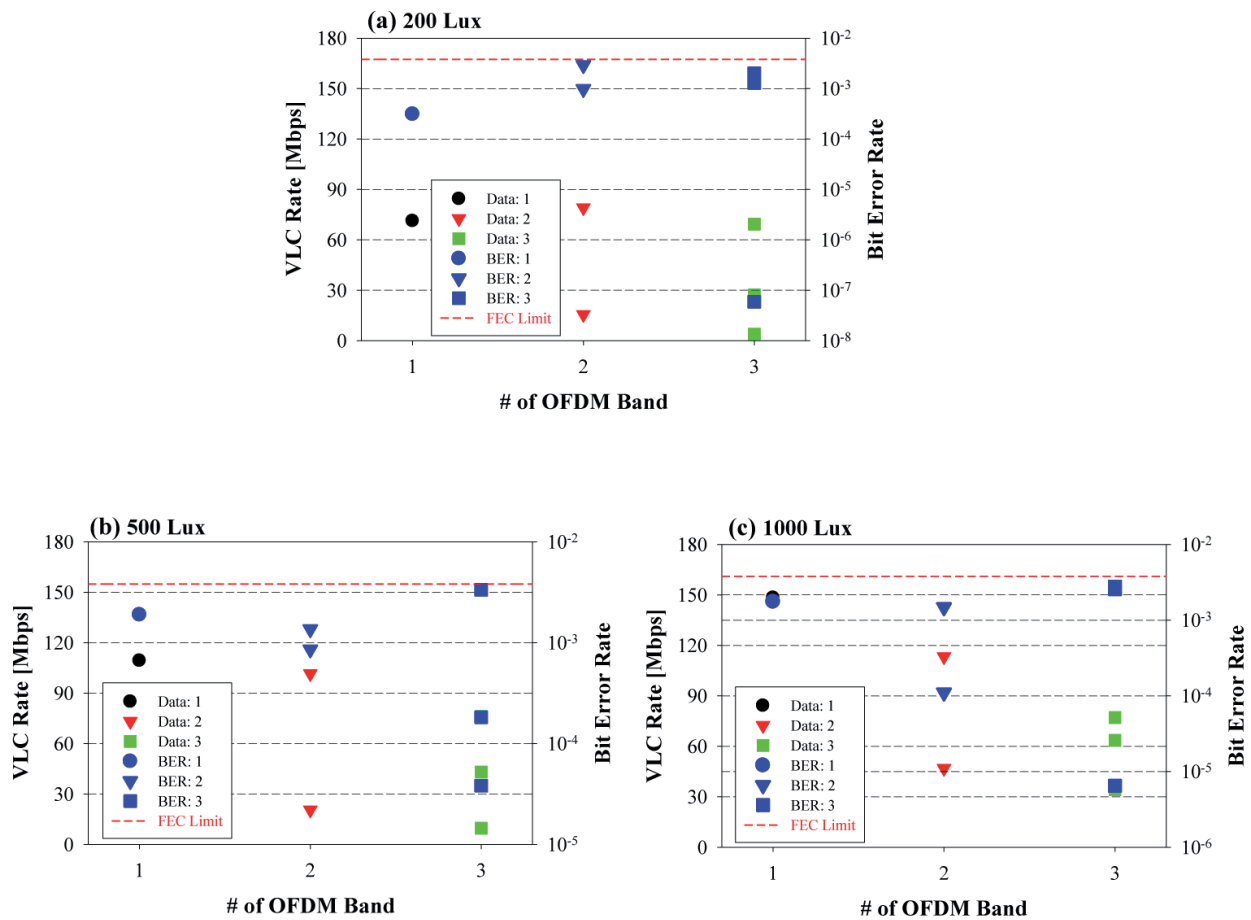
**Figure 3.** Measured frequency response spectrum of phosphor-LED, as the received illumination of Rx-side is 1000 lx.

Then, to understand the connection of VLC illumination and SNR, we utilize the 16-QAM OFDM modulation signal with 30 subcarriers in a frequency bandwidth of 1.95–30.27 MHz for VLC transmission. Based on the observed results of **Figure 3**, using bit-loading 16-QAM OFDM signal to apply on LED luminary for wireless VLC transmission is around the 30 MHz modulation bandwidth. In the measurement, **Figure 4(a)–(c)** presents the measured SNR of each OFDM subcarrier by using single-, dual-, and triple-band OFDM modulations, since the unlike illuminations of 200, 500, and 1000 lx are detected at the client Rx side, respectively. Here, ~20, 26, and 30 MHz available bandwidths can be employed by using multiband OFDM signal, respectively, while the SNR can be greater than 10 dB, under the different illuminations of 200, 500, and 1000 lx, as seen in **Figure 4(a)–(c)**. Compared with the single- and dual-band OFDM formats, the observed SNR characteristics of triple-band OFDM signal is superior in proposed VLC system. If the measured VLC illumination rises increasingly in the client Rx, the observed SNR would also increase under each OFDM modulation format. Moreover, when proposed triple-OFDM band modulation is applied on LED luminary, the measured SNR can improve by 4–21 dB comparing with the single-OFDM band, as depicted in **Figure 4(a)–(c)**. Therefore, when the proposed triple-band OFDM modulation in phosphor-LED VLC system, the all of received SNR also can be increased. In the experiment, the proposed multiband OFDM modulation can be actually enhanced the VLC traffic rate based on the measured results of **Figure 4**. In addition, the related VLC transmission lengths of 2.1, 2.0, and 1.4 m are also executed and measured, as the detected illuminations of 200, 500, and 1000 lx are observed in the Rx, respectively.



**Figure 4.** Experimental setup of the proposed fiber laser scheme in linear cavity scheme.

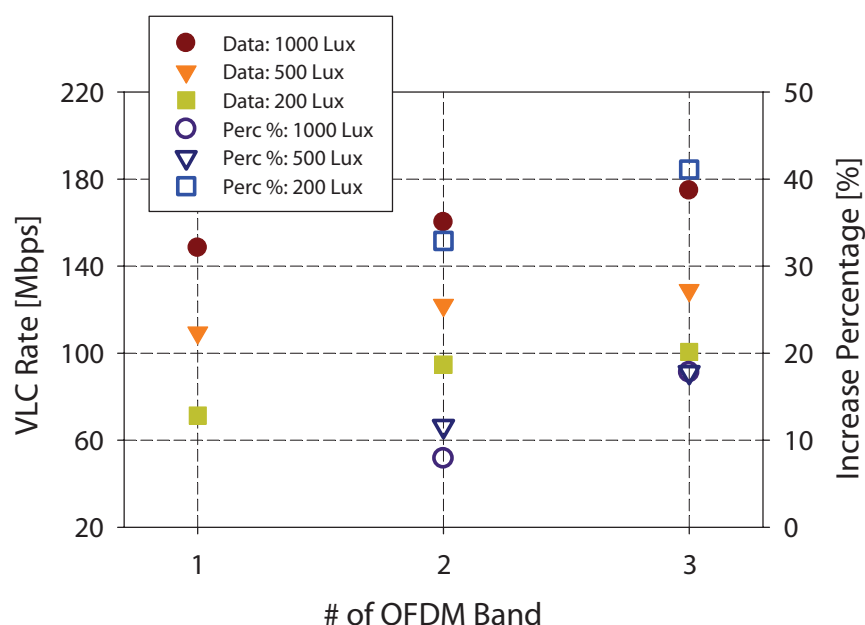
Next, we perform the evaluation of BER experimentally under different observed illuminations. **Figure 5(a)–(c)** shows the measured VLC traffic rate and homologous BER at the observed illuminations of 200, 500, and 1000 lx in the Rx, respectively. Here, the single-, dual- and triple-band OFDM signals are used at the available bandwidth of 1.95–30.27 MHz. As shown in **Figure 5**, if we use the single-band OFDM modulation, the obtained VLC data rates and NERs are 71.3, 109.4, and 148.8 Mbps, and  $3.13 \times 10^{-4}$ ,  $1.89 \times 10^{-3}$  and  $1.76 \times 10^{-3}$ , respectively, under the various illuminations of 200, 500, and 1000 lx. Besides, **Figure 5(a)–(c)** also displays the measured VLC data rate and BER of each sub-band, while the proposed multiband OFDM formats are employed. When we use the dual-band OFDM signal, the VLC rates are 79.1 and 15.6 Mbps (total = 94.7 Mbps), 101.6 and 20.5 Mbps (total = 122.1 Mbps), and 113.3 and 46.9 Mbps (total = 160.2 Mbps), respectively, can be achieved under the different illuminations. The measured BER of each sub-band would be less than that of forward error correction (FEC) threshold ( $\text{BER} = 3.8 \times 10^{-3}$ ), and the average BERs are nearly  $2.60 \times 10^{-3}$ ,  $1.30 \times 10^{-3}$  and  $5.11 \times 10^{-4}$ , respectively. Finally, while we utilize the proposed triple-band OFDM signal in VLC transmission, the VLC data rates of each band and the average BERs are 69.4, 27.3, and 3.9 Mbps, 76.2, 43.0, and 9.7 Mbps, and 77.1, 63.5, and 34.2 Mbps and  $1.71 \times 10^{-3}$ ,  $1.20 \times 10^{-3}$ , and  $1.50 \times 10^{-3}$ , respectively, as shown in **Figure 5**.



**Figure 5.** Measured VLC rate and corresponding BER at the detected illumination of (a) 200, (b) 500, and (c) 1000 lx in the Rx, respectively, while the single-, dual-, and triple-band OFDM modulations are applied.



Finally, we will analyze and discuss the VLC performance of obtained triple-band OFDM signal. **Figure 6** shows the detected total VLC rates and increase percentage of rate at the single-, dual-, and triple-band OFDM modulations, respectively, under the detected illuminations of 200, 500, and 1000 lx. In the experiment, when the proposed dual-band and triple-band OFDM signals are used, the VLC traffic data can reach 94.7, 122.1, and 160.2, and 100.6, 128.9, and 174.8 Mbps, respectively, as seen in **Figure 6**. Hence, the greatest increase percentages of VLC rates of 32.9%, 11.6%, and 7.9%, and 41.1%, 17.8%, and 17.8% are observed, while the various illuminations are 200, 500, and 1000 lx, respectively, and the designed dual-band and triple-band OFDM formats are applied on the VLC transmission. Furthermore, based on the results of **Figure 6**, as the number of OFDM-band increases slowly, the retrieved total VLC traffic rate will also enhance. However, if more sub-band OFDM signal is used in the proposed VLC system, the corresponding cost will be higher. Therefore, the proposed multiband OFDM method can improve and enhance the total VLC rate in phosphor-LED VLC wireless transmission.



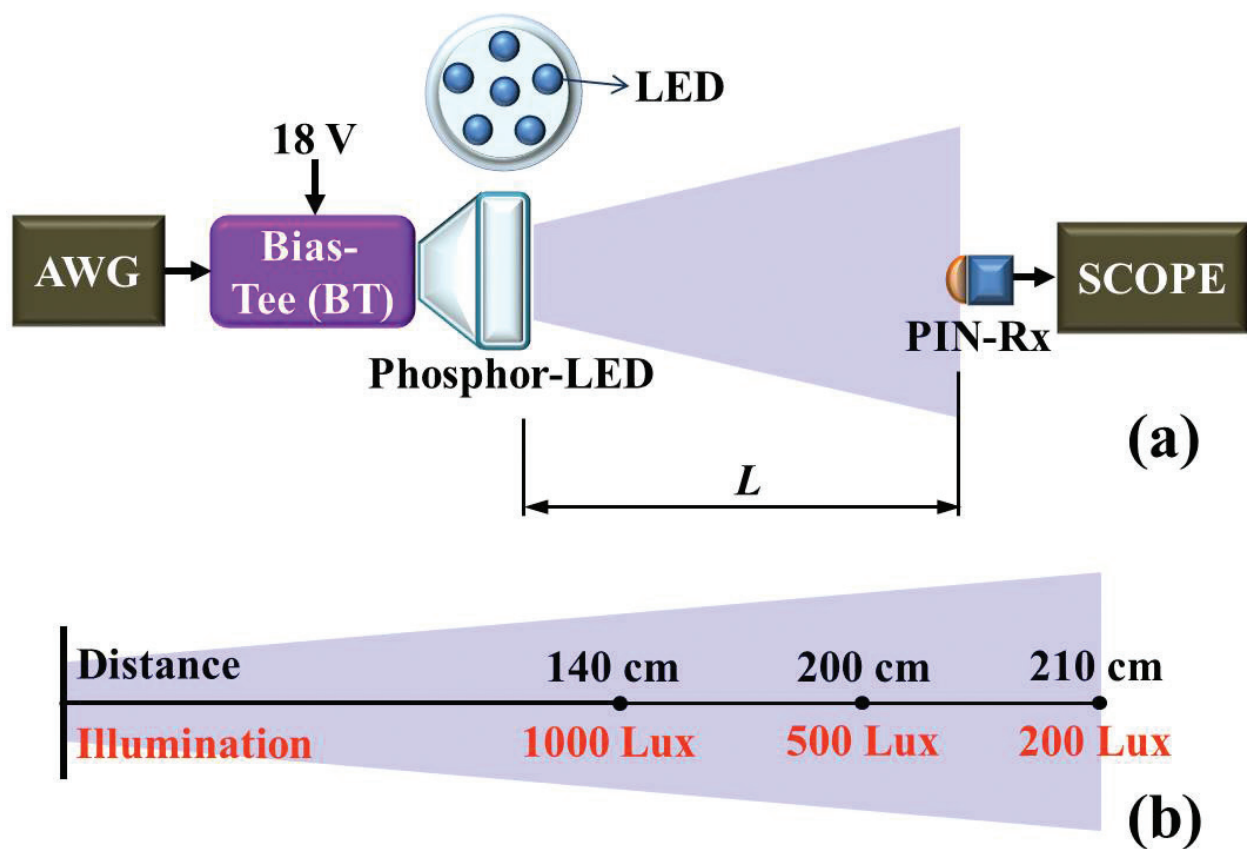
**Figure 6.** Observed total VLC rate and data increase percentage under the single-, dual-, and triple-band OFDM modulation at the observed illuminations.

In summary, the triple-band OFDM format in phosphor-LED VLC system to improve the VLC data rate have been proposed and demonstrated. In this proposed VLC architecture, various signal bands of OFDM formats are applied on unlike LED chips in the same LED luminary. The proposed VLC technology could avoid the power fading and nonlinearity issue by using the same OFDM signal to all the LED chips. In this measurement, we did not use a blue optical filter to enhance the VLC data rate of phosphor-LED. Furthermore, as we use single-OFDM-band modulation in the LED luminary, which has six white-light phosphor-LED chips, the VLC system could reach 148.4 and 71.3 Mbps traffic rates, respectively, when the detected illuminations were 1000 and 200 lx in the client end-user. If we used the proposed triple-band OFDM method at the same detected illuminations, the total VLC rates could be considerably improved to 174.8 and 100.6 Mbps, respectively. Therefore, employing proposed multiband

OFDM modulation could enhance the 41.1% and 17.8% VLC rates in VLC wireless transmission, while the observed illuminations were 200 and 1000 lx, respectively. In addition, the analysis and verification by experiments have been also executed in this section.

### 3. Rate improvement of VLC and real-time half-duplex VLC

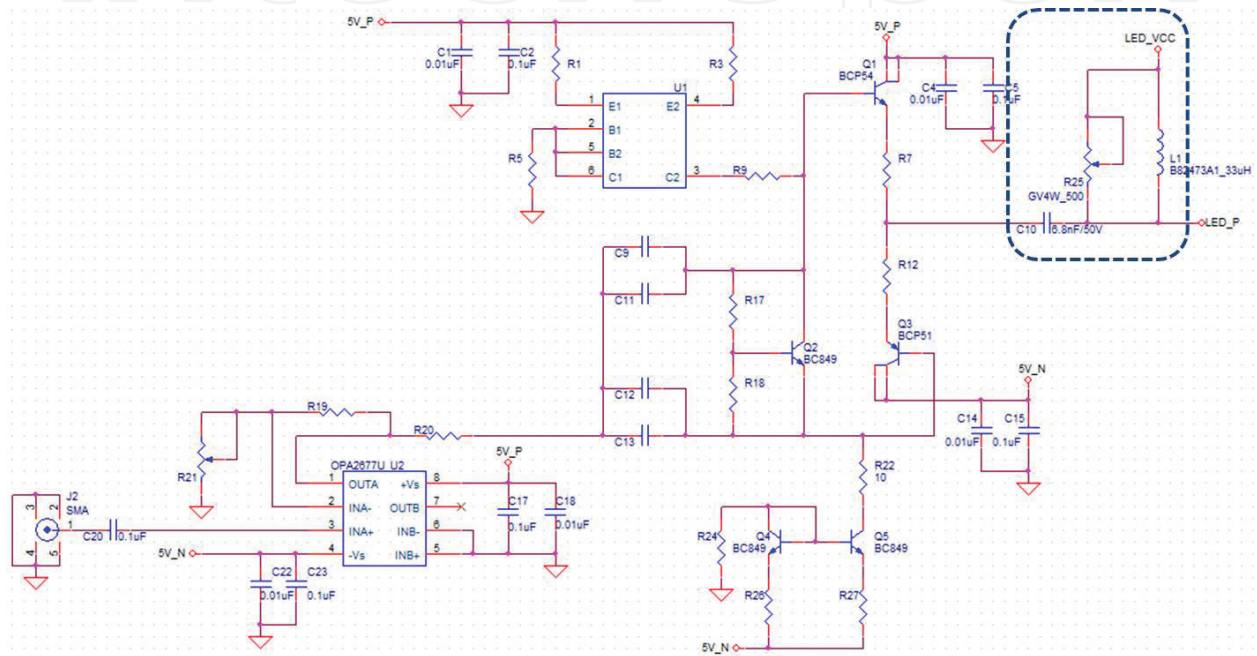
In this section, we introduce and investigate the high-speed phosphor-LED VLC system together with real-time half-duplex transmission [13]. **Figure 7(a)** presents the optical setup of proposed phosphor-LED VLC architecture. In the measurement, a LED luminary with five phosphor-LED chips for acting as the Tx for VLC wireless transmission. **Figure 7(b)** indicates the related illuminations of LED, which is measured by using a light meter (LUTRON lx-1102) at the different transmission lengths in the field of view (FOV) in proposed VLC transmission system. As the measured illuminances are 200, 500, and 1000 lx, respectively, the corresponding free space transmission lengths of 210, 200, and 100 cm, are also obtained as shown in **Figure 7(b)**.



**Figure 7.** (a) Proposed phosphor-LED VLC wireless system. (b) Corresponding illuminations under different transmission lengths in the field of view of the proposed VLC.

In the VLC-Tx side, the LED luminary has five phosphor-LED chips for lighting and communication. Here, each LED chip is covered by a lens with divergent angle of  $45^\circ$ . Besides, an imaging lens in front of the client Rx is used for focusing and enhancing the detected VLC power. To

reach a higher VLC data capacity in phosphor-LED VLC system, we can utilize OFDM-QAM modulation format with bit-loading, which is directly applied on the LED luminary by using proposed BT circuit, as shown in **Figure 8**. The resistance ( $R$ ) of BT circuit is nearly  $3\ \Omega$ . The proposed BT circuit without complicate pre-equalization design has been also demonstrated in Ref. [28]. Hence, we adapt the resistance ( $R$ ), inductance ( $L$ ), and capacitance ( $C$ ) suitably for matching the impedance of five LED chips in the LED-Tx side. The AC modulated signal can be generated by the AWG and is connected to the “SMA” port at the lower left corner of **Figure 8**, whereas the LED is linked to the “LED\_P” port at the upper right corner of **Figure 8**.

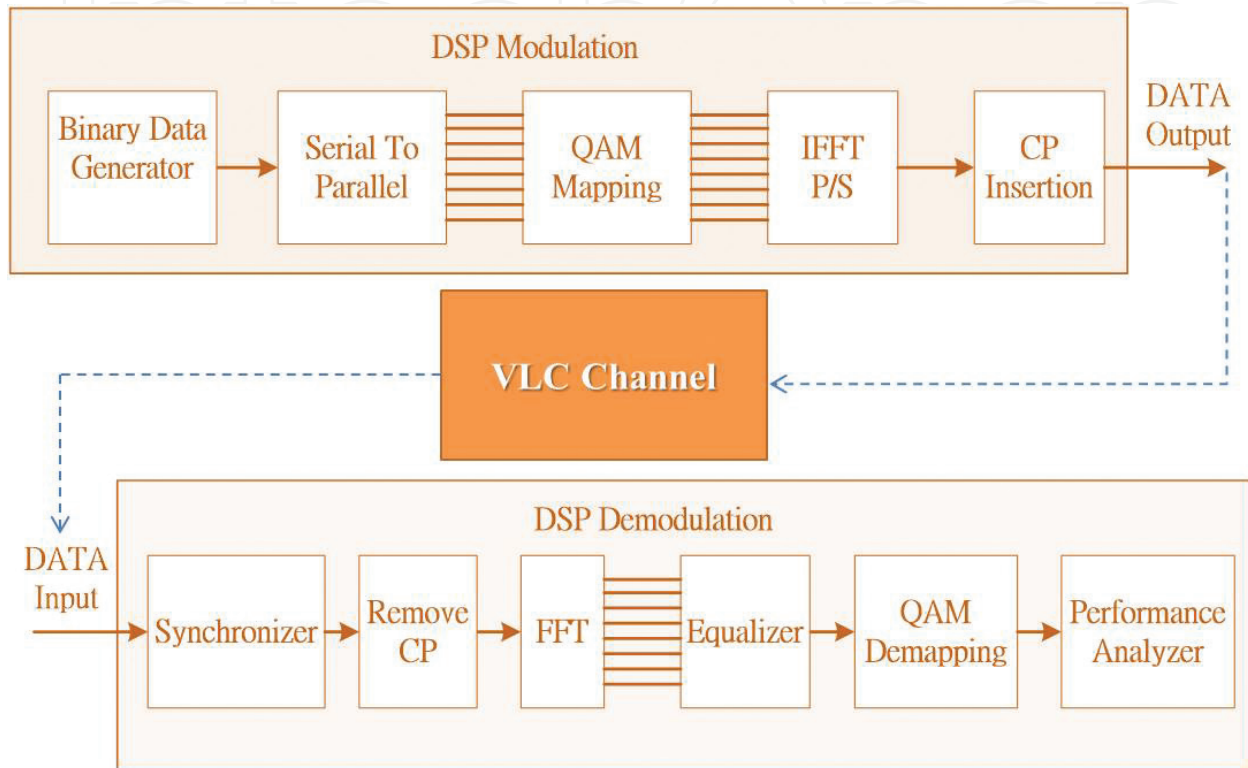


**Figure 8.** The proposed BT circuit topology.

In the experiment, we employ the five white-light phosphor-LED chips with series connection scheme for indoor illumination. Therefore, the OFDM-QAM signal can be applied on the LED luminary for direct modulation by employing an arbitrary waveform generator (AWG) for VLC wireless communication. In **Figure 7(a)**, the white-light VLC signal emits from the LED-Tx and detected by using the silicon-based PIN Rx. Then, the detected VLC signal will be amplified through a wideband RF amplifier (Picosecond 5867), and connected to a real-time oscilloscope for VLC signal demodulation.

In the measurement, the OFDM-QAM, which uses bit-loading algorithm, and the OFDM symbol can be encoded offline using the MATLAB program. The flow diagram for proposed OFDM-QAM algorithm is shown in **Figure 9**. The serial binary stream can be converted into several parallel streams, and each parallel binary flow is plotted into 16-QAM symbols. The inverse fast Fourier transform (IFFT) process with 256 IFFT size is executed on the QAM symbols to create the digital OFDM symbols. Cyclic prefix (CP) of  $1/32$  will be added in each OFDM symbol to reduce the dispersion-induced characteristic deprivation. The encoded digital OFDM

symbol can be delivered into an AWG and altered into analogue electrical signal via the digital-to-analogue converter (DAC). Here, we use the 250 Msample/s sampling rate and 8-bit DAC resolution from the AWG for measurement. Then, in the Rx-side, the VLC wireless signal can be directly detected via a PIN-PD, which is linked by a real-time oscilloscope with sampling rate of 250 Msample/s for VLC signal decode. Finally, the VLC OFDM signal can be demodulated offline by retreat process of the encoder.



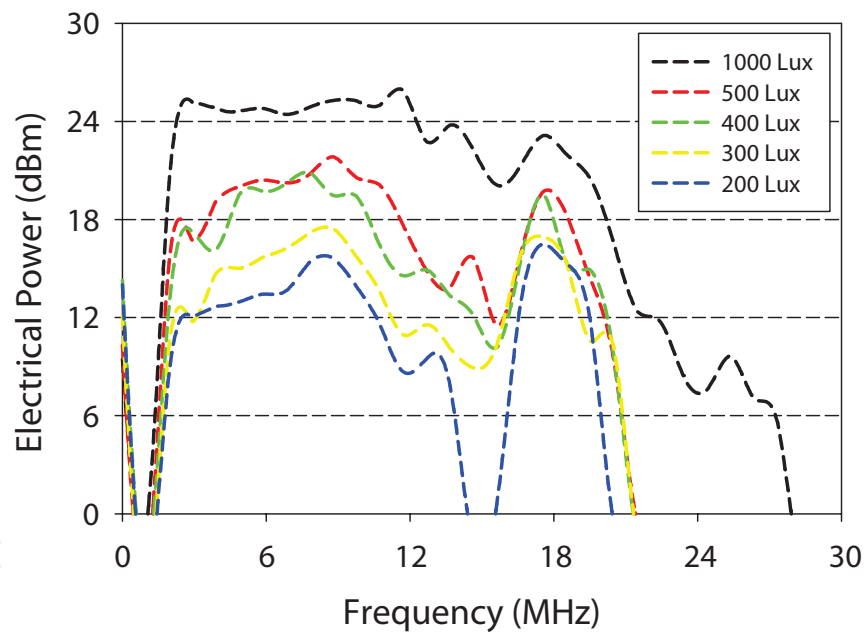
**Figure 9.** The flow chart of OFDM-QAM algorithm.

**Figure 10** presents the observed electrical power spectra of phosphor-LED at the various detected illuminances of 200, 300, 400, 500, and 1000 lx, respectively. And the measured response frequency regions are around 20, 21, 21, 21, and 27 MHz, respectively, as depicted in **Figure 10**. When we decrease the illuminance of client side gradually, the relative powers will also reduce, as shown in **Figure 10**. Furthermore, the available electrical power range will fall rapidly in a higher frequency region, as seen in **Figure 10**. As we know, the smaller electrical power would lead to the poor SNR of each OFDM subcarrier. Thus, the corresponding VLC traffic rate would be restrained in the frequency bandwidth. In the measurement, the SNR is observed from the measured constellation of Rx-side. Moreover, in digital modulation applications, the SNR can be stated usually by measuring the modulation-error ratio from constellation information.

Then, **Figure 11(a)** displays the measured SNR of each OFDM subcarriers using 16-QAM modulation format in the different illuminances of 200, 300, 400, 500, and 1000 lx, respectively. Moreover, we utilize 30 OFDM subcarriers in the modulation range from 1.95 to 30.27



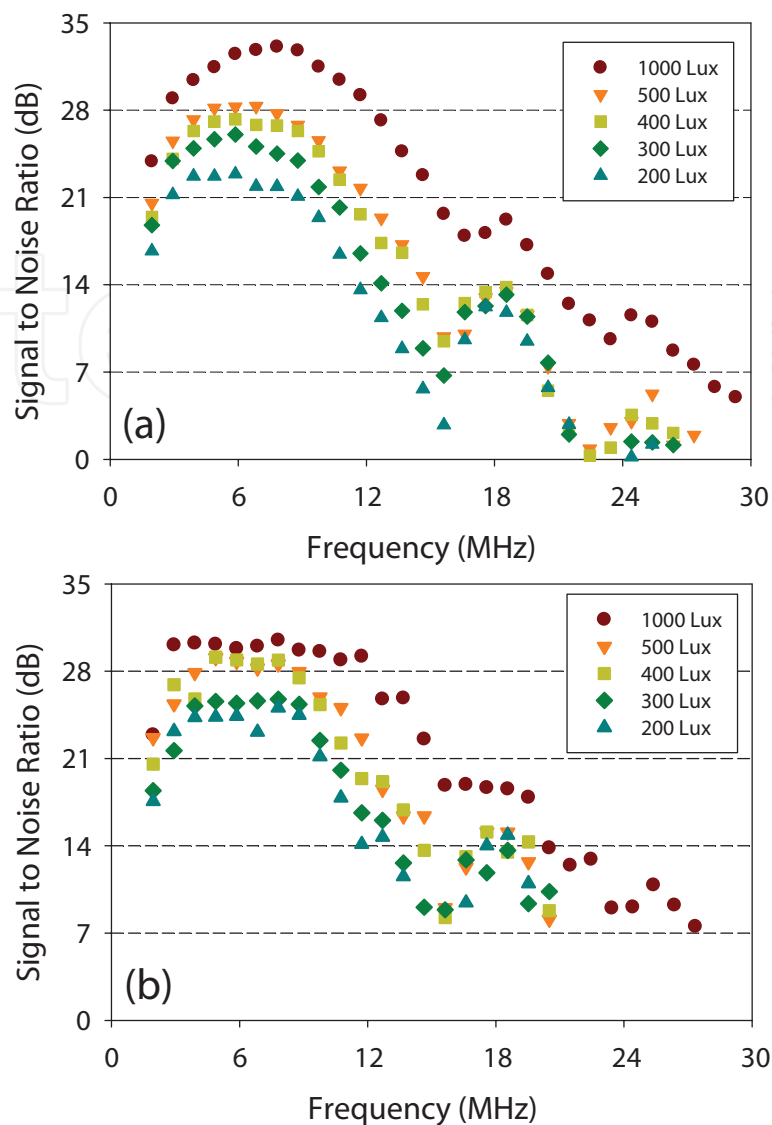
MHz for creating VLC OFDM signal. To completely employ the unflatten SNR, the modulated signal of each OFDM subcarrier can be adapted with bit-loading algorithm based on the obtained SNR value. While we use the bit-loading with QAM order from 4 to 256, the measured SNR spectra can be obtained, as shown in **Figure 11(b)**. Hence, each OFDM subcarriers with their corresponding SNRs are among 9.4 and 25.1, 15.6 and 25.7, 8.3 and 29.1, 8.1 and 29.1, and 7.5 and 30.5 dB in the frequency regions of 1.95–19.53, 1.95–20.50, 1.95–20.50, 1.95–20.50, and 1.95–26.36 MHz, when the obtained illuminances are 200, 300, 300, 400, 500, and 1000 lx, respectively. Here, the measured corresponding constellations of 4, 16, and 256 QAM under the results of **Figure 11(b)** at 500 lx state are illustrated in **Figure 12**. Therefore, the available modulation range can achieve nearly 27 MHz by using the proposed LED-Tx unit. In addition, the frequency bandwidth can be defined as the available bandwidth. The obtained SNR can satisfy the FEC (i.e.,  $\text{BER} = 3.8 \times 10^{-3}$ ) requirement when the bit-loading OFDM is utilized. The useful bit range of the algorithm is adjusted between 4- and 128-QAM adaptively, thus the available frequency range can support at least 4-QAM data traffic (i.e.,  $\text{SNR} = \sim 8$  dB).



**Figure 10.** Observed electrical power spectra at the various detected illuminances of 200, 300, 400, 500, and 1000 lx, respectively.

Furthermore, the measured VLC data rates are 71.3, 89.8, 102.5, 109.4, and 148.4 Mbps, respectively, under the different illuminances of 200, 300, 400, 500, and 1000 lx, as also shown in **Figure 13**. In this measurement, all of the measured corresponding BERs are below the FEC threshold under the various detected illuminances, as illustrated in **Figure 13**. In addition, the FEC threshold was also determined as Ref. [29]. FEC would indicate 7% overhead which is used for the coding to measure error-free in the proposed VLC wireless system.

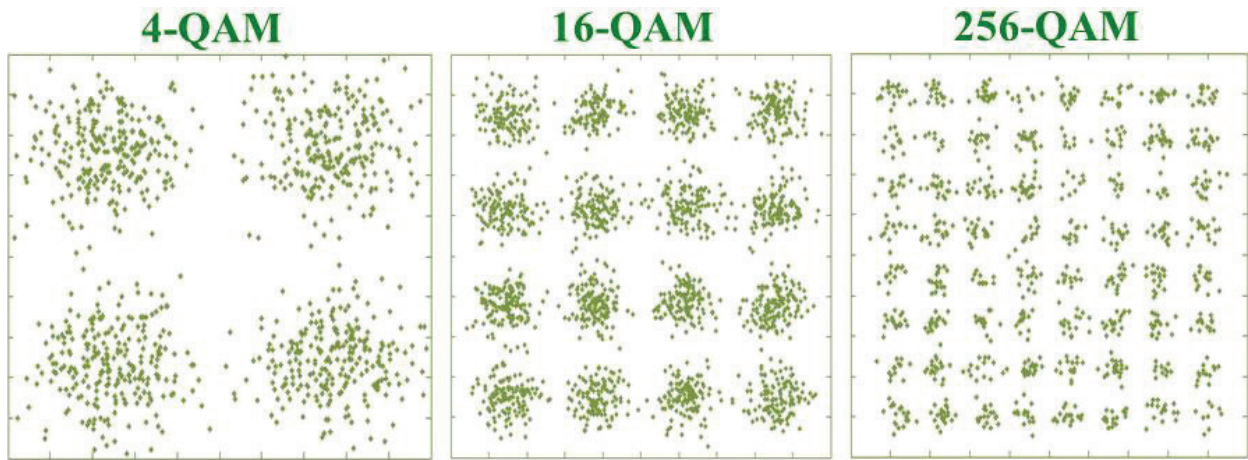




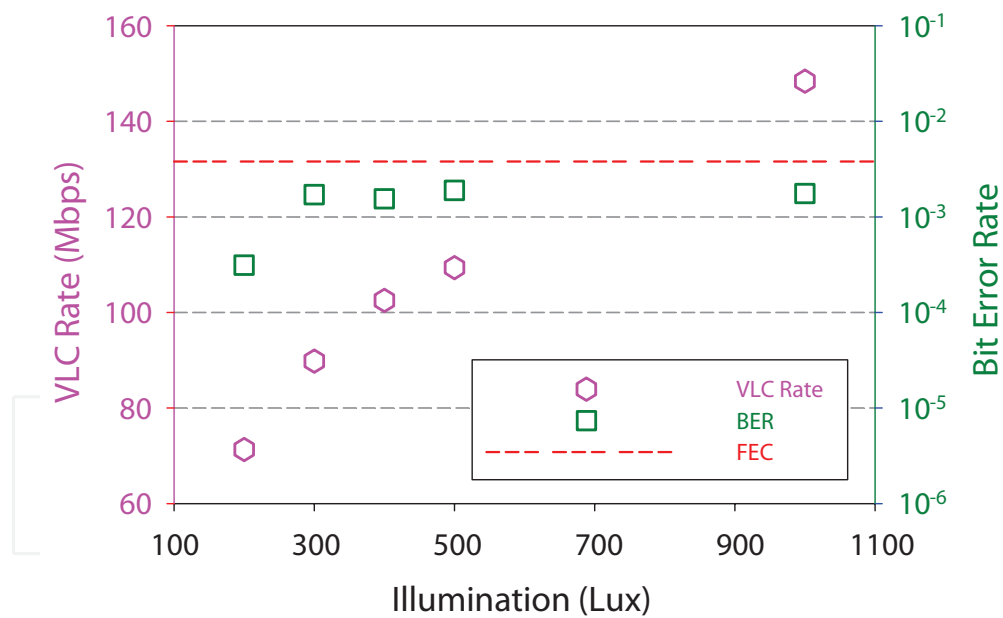
**Figure 11.** Measured SNR spectra of each OFDM subcarrier (a) without and (b) with bit-loading at the detected illuminances of 200, 300, 400, 500, and 1000 lx, respectively.

Then, a real-time bidirectional phosphor-LED VLC transmission is also proposed and demonstrated. Here, the commercial OFDM-based DSP chip is applied in the Tx and Rx simultaneously sides to replace the AWG and oscilloscope for encoding and decoding VLC channel. However, the commercial DSP chip only has half-duplex transmission function for VLC. In the real-time DSP VLC transmission, we use a commercial DSP chip and Ethernet port for VLC signal processing and connecting, respectively. The modulation bandwidth of DSP chip is from 2 to 100 MHz with adaptively OFDM-QAM formats from QPSK to 16-QAM. The maximum data rate could reach 250 Mbps via the OFDM DSP chip. In the measurement, five phosphor-LED chips in the LED-Tx side carry the same modulated data for VLC transmission. The VLC channel was analyzed and discussed fully in Ref. [2], while the modulation rate of the demonstration was low, the crosstalk influence could be ignored. If some LEDs are utilized in the DC mode or AC mode for VLC transmission, they could generate the background noises affecting

the VLC performance within the frequency of 2 MHz, as investigated in Ref. [30]. Hence, the OFDM DSP chip can be used in VLC system to avoid the low-frequency noise interference.



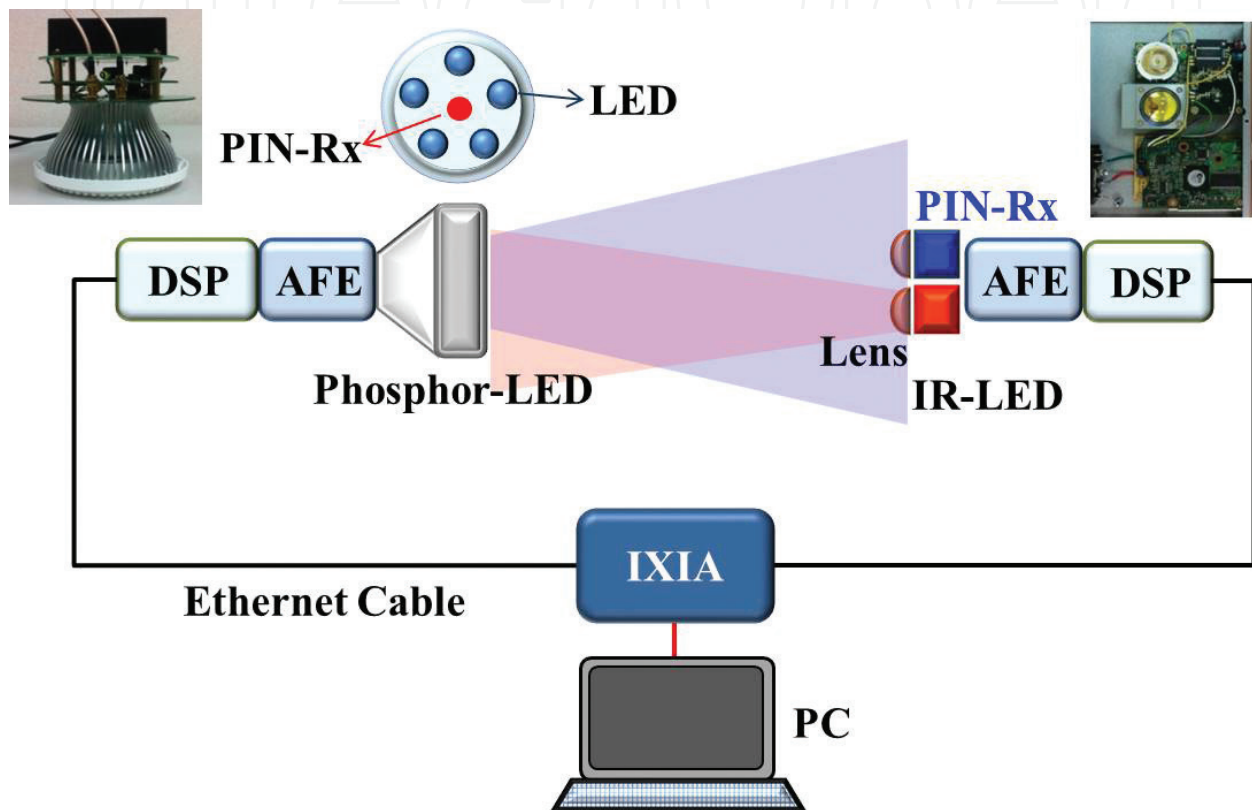
**Figure 12.** The obtained corresponding constellations at 500 lx of the result in **Figure 11(b)**.



**Figure 13.** Measured VLC traffic rates and related BERs under different detected illuminances.

**Figure 14** presents the new proposed setup of real-time bidirectional phosphor-LED VLC transmission system. In the LED luminary, five phosphor-LED chips with series connection are driven at 15 V for illumination and VLC transmission. In the experiment, the LED Tx-side and client side both contains the analog front-end (AFE) and DSP parts for signal encoding and decoding, as shown in **Figure 14**. Here, we add an infrared (IR) PIN-Rx in the LED luminary, as

shown in **Figure 14**, to detect the upstream IR wireless signal emitted from the client end-user. An 850 nm IR-LED with 40 MHz modulation bandwidth is used in client side to act as the upstream emitter for upstream traffic signal. The emission angle of IR-LED is set at 30°. Besides, a PIN-Rx, having 50 MHz bandwidth in the client side, is used to receive the downstream VLC traffic. Here, we also add the lenses in front of each Tx and Rx for maximizing the performance of VLC signal, as also shown in **Figure 14**. In this work, an 850 nm IR-LED is employed serving as an upstream channel for real-time bidirectional VLC transmission.

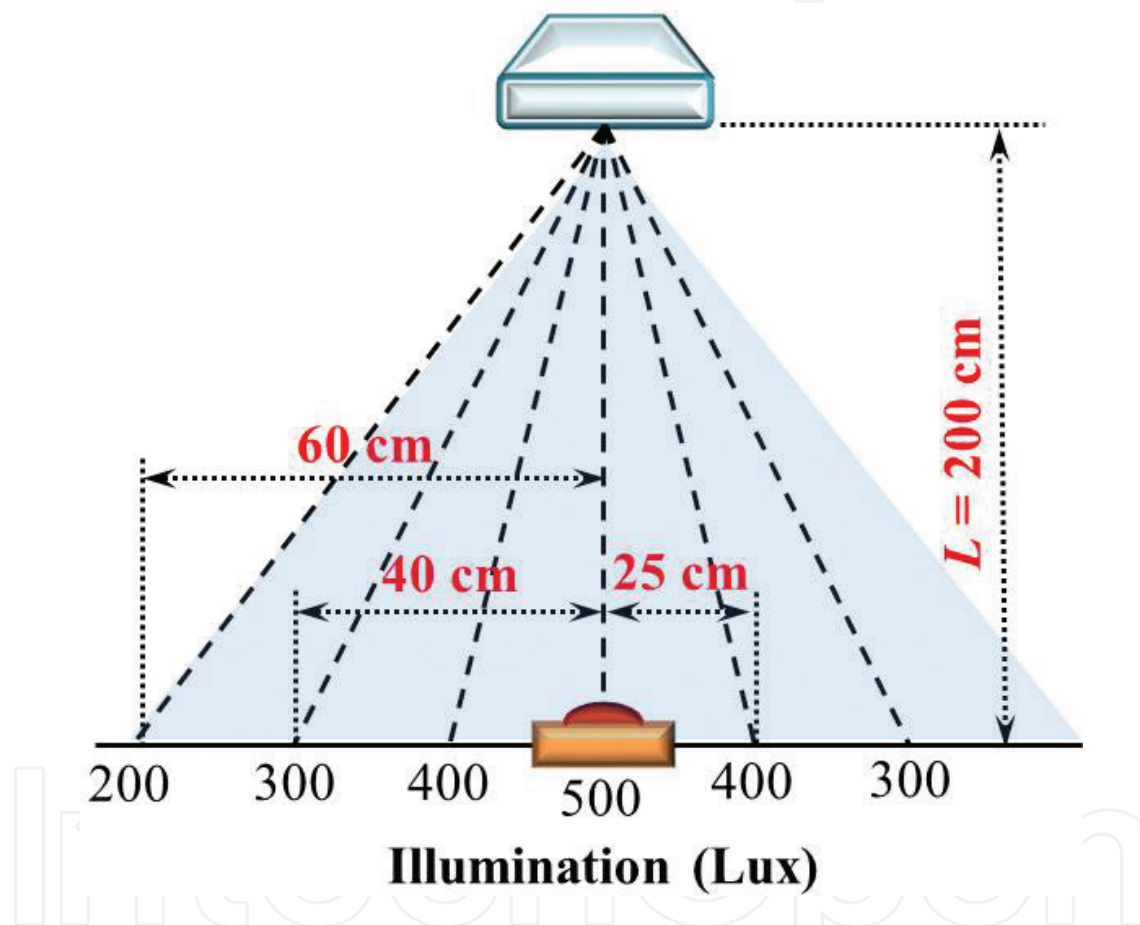


**Figure 14.** New proposed real-time bidirectional phosphor-LED VLC transmission system.

Furthermore, to understand the connection of the lighting illuminance and the horizontal location of the client side, the VLC vertical transmission distance is set at 200 cm in the central position, as shown in **Figure 15**. And the proposed user client module can be changed at various horizontal positions for detecting VLC signal, as shown in **Figure 15**. In the proposed VLC system, if the horizontal positions are 0, 25, 40, and 60 cm, as depicted in **Figure 15**, respectively, the corresponding illuminances are measured at 500, 400, 300, and 200 lx. In addition, to execute and evaluate the performance of proposed real-time VLC transmission, a network analyzer (IXIA 1600T) is used to test the IP-based throughput for real-time data traffic. Here, a 70 Mbps testing rate of network analyzer can be utilized in the half-duplex VLC transmission for performing VLC performance.

The downstream throughput performance can be performed in relation to the VLC setup of **Figure 15**. Here, the illuminance is 500 lx, when the vertical transmission length is 200 cm.

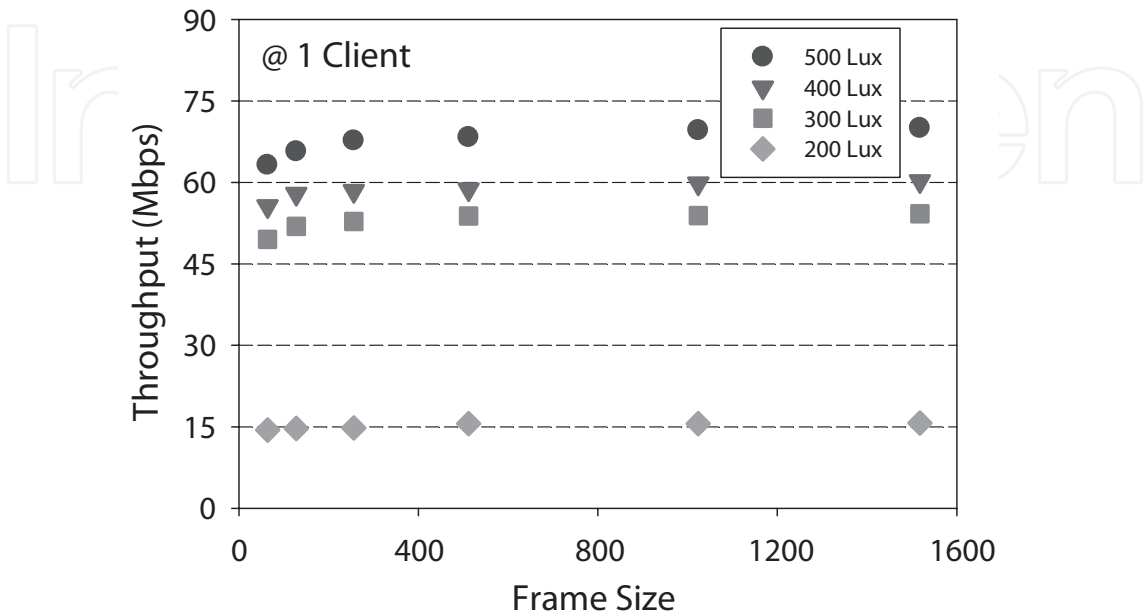
**Figure 16** displays the downstream throughputs under the different data frame sizes of 64, 128, 256, 512, 1024, and 1518, respectively, while the client module is placed to 60 cm away from center location. Hence, we can understand the corresponding illuminance for receiving and decoding the VLC signal under different location. Thus, the illuminances of 500, 400, 300, and 200 lx are measured, when the related horizontal locations are 0, 25, 40, and 60 cm, respectively. Moreover, while the data frame size rises increasingly, the measured traffic throughputs also enhance, as shown in **Figure 15**. The measured throughputs are 15.7, 54.2, 60.2, and 70.0 Mbps under the illuminances of 200, 300, 400, and 500 lx at the 1518 frame size. If the frame size is set at 64, the measured throughputs will be 14.4, 49.5, 55.6, and 63.2 Mbps, respectively.



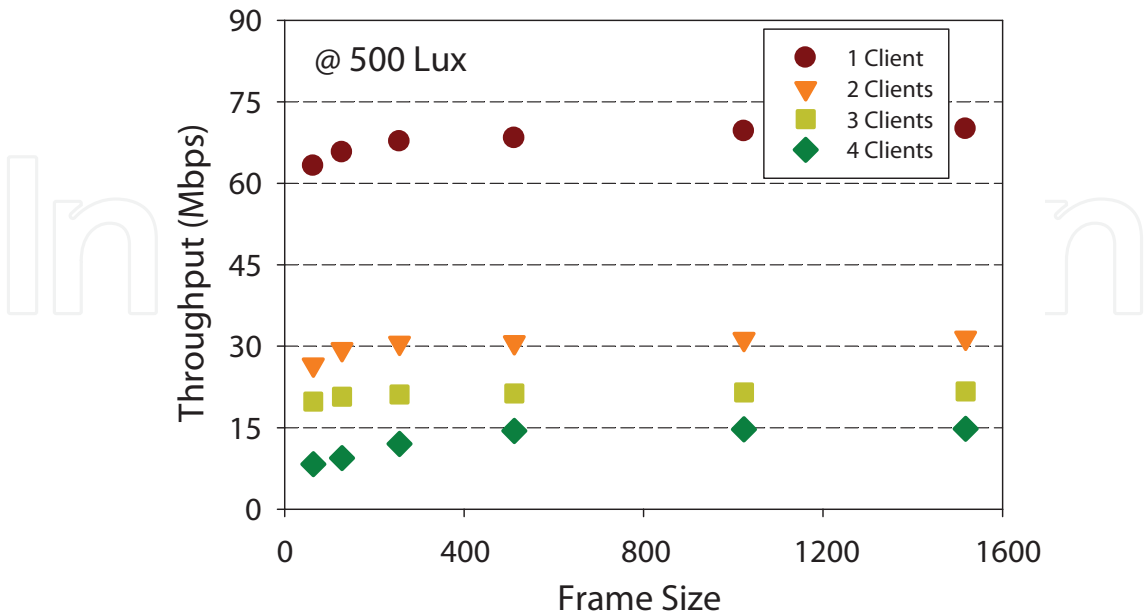
**Figure 15.** Observed illuminances in the client side at various horizontal positions under a 200 cm vertical transmission distance.

Moreover, to comprehend the practical VLC performance, one to four client modules are used in the same setup of **Figure 15**. Here, the illuminance is set at 500 lx. **Figure 17** present the downstream throughputs under different data frames of 64, 128, 256, 512, 1024, and 1518, respectively, while one to four client modules are employed at the tested LED luminary for measuring VLC traffic. As seen in **Figure 17**, while the frame data size is raised gradually, the retrieved data throughputs also improve. When one client module is utilized in the VLC system, the observed VLC efficiency is the same as **Figure 16**. As the client number increases,

the relative throughput would be decreased, as shown in **Figure 16**. While the frame size is 1518, the observed throughput is 70.0, 31.5, 21.7, and 14.8 Mbps, respectively, if one to four client modules are also employed.



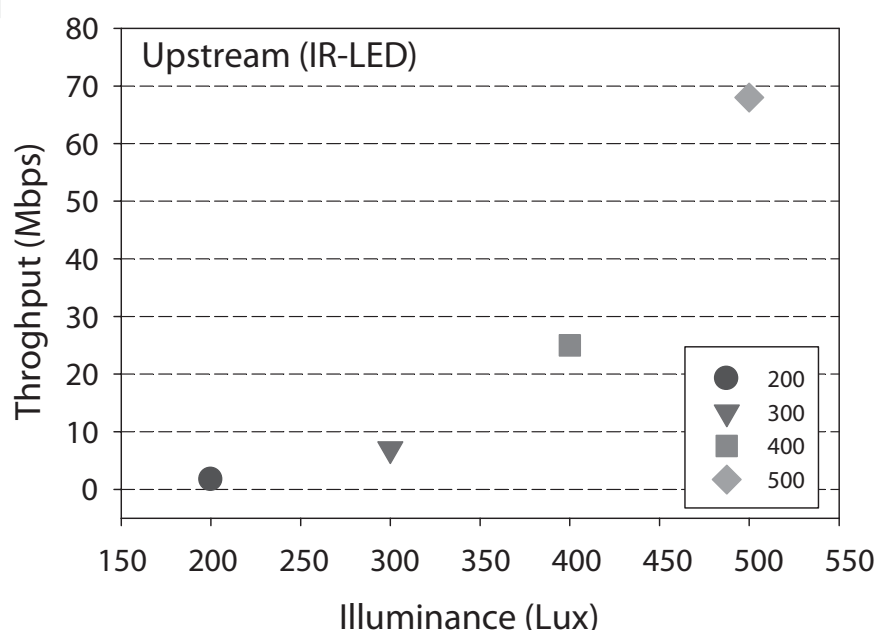
**Figure 16.** Measured downstream throughputs under the various data frame sizes, when a client module is move outward from central point to 60 cm (200 lx).



**Figure 17.** Measured downstream throughput spectra under various data frame sizes of 64, 128, 256, 512, 1024, and 1518, respectively, when one, two, three, and four client modules are used.



Finally, we also execute the 850 nm IR-LED upstream traffic in a 200 cm vertical transmission distance. In this experiment, the real setup is the same as in **Figure 15**. The client module is moved away from the center position to 25, 40, and 60 cm, respectively, for upstream throughput measurement. **Figure 18** shows the maximum upstream throughput with random frame size from 1.7 to 70 Mbps under different illuminances of 200–1000 lx. Therefore, when the commercial half-duplex DSP chip is applied in LED VLC system, the VLC traffic can reach 70 Mbps for real-time bidirectional transmission.



**Figure 18.** Observed upstream data rate under different detected illuminances in the proposed real-time VLC system.

In summary, we proposed and investigated a 71.3–148.4 Mbps white phosphor-LED VLC system in the free space transmission distance of 140–210 cm in the different illuminances of 200–1000 lx, respectively. Here, a white-light LED luminary, having five cascaded LED chips, was utilized for indoor illumination and wireless access simultaneously. Here, we used the bit-loading OFDM-QAM modulation signal and a novel bias-tee circuit in AFE to improve the modulation bandwidth from 1 to 27 MHz. In addition, we did not utilize a blue optical filter in the client side for improvement. To understand and demonstrate the real-time wireless VLC performance in the proposed phosphor-LED VLC system, a commercial OFDM-based DSP chip was used in the LED lighting side and client sides, simultaneously. Here, the OFDM-DSP chip would result in half-duplex operation. In this investigation, we used a network analyzer to measure the throughput of practical VLC data in the proposed VLC system at different illuminances. As a result, the proposed real-time bidirectional VLC system could accomplish the 70 Mbps data throughputs in a practical transmission distance of 200 cm at the luminance of 500 lx.

## 4. Conclusion

In conclusion, we reviewed our recent works on the phosphor white-light LED-based wireless VLC and its practical applications. This chapter was divided into two sections. In the first section, to enhance the transmission rate in phosphor-LED VLC system, we proposed and demonstrated a novel multi-band OFDM modulation format for capacity enhancement. According to the proposed architecture, different bands of OFDM signals were used to different LED chips of the LED luminary; it can avoid the power fading and nonlinearity effects of transmission signal by using the same OFDM signal to the whole LED chips. Hence, the maximum enhanced percentage of VLC data rate was 41.1% when the proposed new multi-band OFDM modulation was used.

In the second section, we also demonstrated a 71.3–148.4 Mbps phosphor-LED wireless VLC system at the free space transmission distance between 140 and 210 cm. Moreover, a commercial white-light phosphor-LED luminary with five phosphor-LED chips in series was used for illumination and communication, simultaneously. Here, optical OFDM signal with bit-loading algorithm was applied for VLC transmission. We also investigate an optimal bias-tee circuit with equalization to improve the modulation bandwidth from 1 to 27 MHz. Finally, to understand and demonstrate the real-time LED VLC transmission, a commercial OFDM-based DSP chip was used in the LED transmitting side and client side, simultaneously. Therefore, the proposed real-time half-duplex VLC system could complete around 70 Mbps downstream and upstream traffic throughputs, in a free space transmission distance of 200 cm long for practical in-home illumination and smart city applications.

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