

# Chapter 4

## Visible Light Communication

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### 4.1 Worldwide VLC Activities

Visible light communication(VLC) is a kind of optical communication using visible wavelength of the electromagnetic spectrum from 380 to 780 nm. VLC based on light emitting diode (LED) lamps has attracted much attention recently for the future secure and high speed data transmissions. The continuous improvement in power efficiency and cost reduction have made LED lamp gradually replacing the traditional lamps. According to the IMS Research, by 2013, the LED lamp market is the largest in the lighting market, and has 40 % market share of the total [1]. The IMS Research has forecast there will be a significant increase in LED lamp sales in coming years due to the “banning” of incandescent lamps in many countries [1].

LEDbased VLC provides many transmission advantages, making it a promising technology for future short-range communication. One advantage offered by VLC is that it is using the visible electromagnetic spectrum, which is not regulated, or license-free. Hence, it is relatively easy to develop new products for VLC. Besides, VLC can be used to broadcast real-time traffic information using traffic lights to the vehicles; hence, drivers can be updated continuously for the real-time traffic conditions [2]. Moreover, it can be a secure channel between different

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mobile devices, since the light beam is visible and users can securely limit the coverage of illumination for communication. In addition, VLC does not penetrate through walls; hence, there is no interference among users in different rooms [3]. VLC is also desirable to provide optical wireless communication (OWC) in some areas where radio frequency (RF) communication is prohibited, such as in hospitals or aircrafts. In addition, radio waves do not propagate for a long distance under water; hence VLC is particularly suitable for under water communication [4]. Apart from communication purposes, VLC can be used in a three dimensional position measuring system with high accuracy [5, 6].

As mentioned before, VLC offers many transmission advantages and it has attracted much attention recently. VLC is being extensively studied by a number of universities and companies worldwide. In November 2003, the Visible Light Communication Consortium (VLCC) was established in Japan to explore different applications of VLC. It invited companies to contribute in VLC development [7]. In 2007, the VLCC proposed two standards: Visible Light Communication System Standard and Visible Light ID System Standard to the Japan Electronics and Information Technology Industries Association (JEITA), which then accepted these standards as JEITA CP-1221 and JEITA CP-1222 [8]. In 2008, the OMEGA Project [9] funded by the European Commission under the Seventh Research Framework Program (FP7) started to develop a home area network capable of delivering high-bandwidth services and content at a transmission speed of 1 Gb/s. The OMEGA Project consisted of 20 European partners from industries and academia. In 2010, the Center for Ubiquitous Communication by Light (UC-Light) was established in the United States [10]. Its mission was to enable wireless communications by embedding signals into the light emitted by next-generation LED systems. Besides, the Smart Lighting Engineering Research Center was established to promote researches leading to smart lighting systems with adaptive and controllable properties [11]. Communication using light to send information and enable lighting information processing was within the scope of the Smart Lighting Engineering Research Center. In 2011, an international platform, called Li-Fi Consortium was formed [12]. Its goal was to foster the development and distribution of optical wireless technologies such as communication, navigation, natural user interfaces and others. An IEEE standard (IEEE 802.15.7—Short-Range Wireless Optical Communication Using Visible Light) was finalized in 2011 [13], enhancing the prospects for commercializing VLC. The standard covers both the physical (PHY) layer interface and the medium-access control (MAC) layer. However, several aspects, such as flicker mitigation, dimming control, implementation of advanced modulations, background noise mitigation, and effective bi-directional transmission have not been specified [14]; and further research and development for the VLC are still going on.

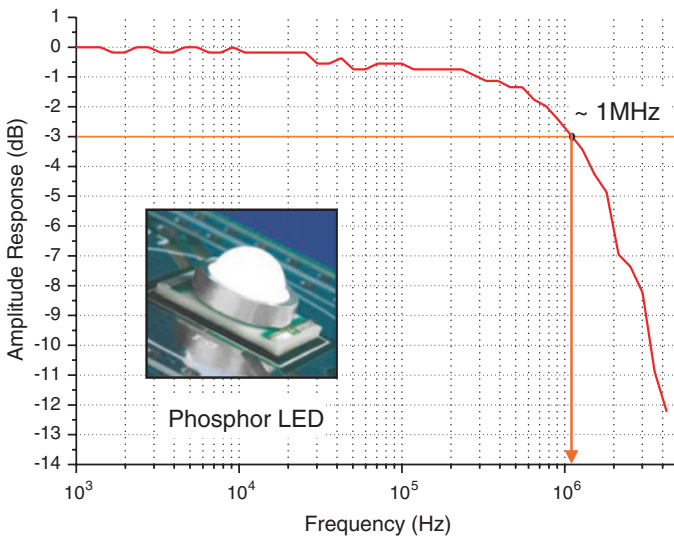
In this chapter, we discuss different technical aspects (the challenges and possible solutions) of VLC, which include enhancing the transmission data rate of VLC, mitigation of the optical background noises, achieving a bi-directional transmission, and using AC-LED for VLC. Finally, a conclusion was presented to summary the section.

## 4.2 Different Technical Aspects of VLC

### 4.2.1 Enhancing Transmission Data Rate

When the VLC is incorporated into the lighting system, white-light LED is need. There are two kinds of white LED used in general lighting. One type consists of a blue LED chip with a phosphor layer on top of it. The emitted blue light is partly absorbed by the phosphor layer to produce yellow light. Hence, the blue and yellow lights result in white light. Another type of white LED is fabricated using three primary colored chips: red, green and blue (RGB). The combination of the RGB produces white light. The phosphor-based LED is low cost, but the limited response time of phosphor makes the direct modulation speed of this phosphor-based LED only a few MHz. On the other hand, the RGB white LED is higher cost; however the direct modulation speed of each chip can be as high as several tens of MHz.

When using the phosphor-based LED for VLC, a blue optical filter at the receiver (Rx) is used to remove the slow yellow component. However, this increases the attenuation of the VLC transmission link and decreases the transmission distance and performance. Electrical pre-equalization or post-equalization for the LED driving and Rx circuits can be used [15–22] respectively to enhance the transmission data rate of the VLC. Yeh et al. [23] demonstrated using quaternary-amplitude-shift-keying (4-ASK) modulation and digital filtering to increase the transmission data rate of a white-light LED VLC system by 20 times. A white-light LED commercially available for lighting application with a direct modulation speed of 1 MHz was used. Figure 4.1 shows the normalized frequency response of the white phosphor-based LED used in the experiment.



**Fig. 4.1** Normalized frequency response of the white phosphor-based LED used in [23]

Figure 4.2 shows the diagrams for generation of the 4-ASK modulation format. The binary data logic sequence was mapped to the 4-ASK symbol having different amplitude levels. The up-sampling process increased the sampling rate by inserting zeros between the original sample points. Then, the digital finite impulse response (FIR) filter provided a frequency domain compensation for the system channel response. Besides, matched square-root raised cosine (SRRC) filters were used in the transmitter (Tx) and Rx, respectively.

Figure 4.3 shows the experimental bit-error-rate (BER) measurement by using the proposed scheme. No optical blue filter was used in this experiment. A clear and wide open 4-ASK eye diagram can be achieved, as shown in Fig. 4.3a, in which the total transmission data rate was 20 Mb/s and the transmission length was 1 m. BER of  $<10^{-10}$  can be achieved. Figure 4.3b shows the eye diagram without using the proposed scheme. The measured eye-diagram was completely

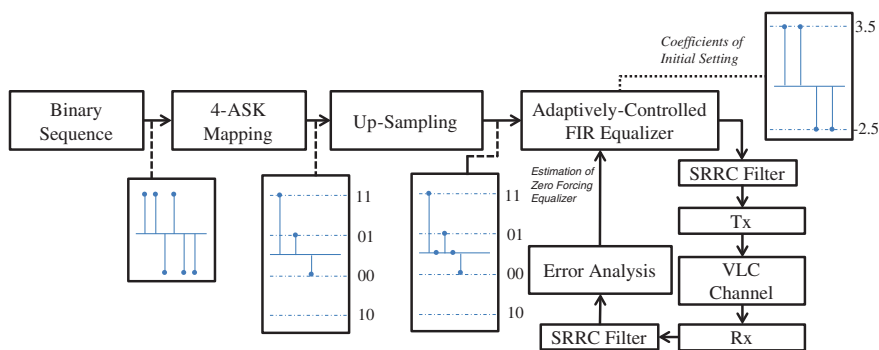
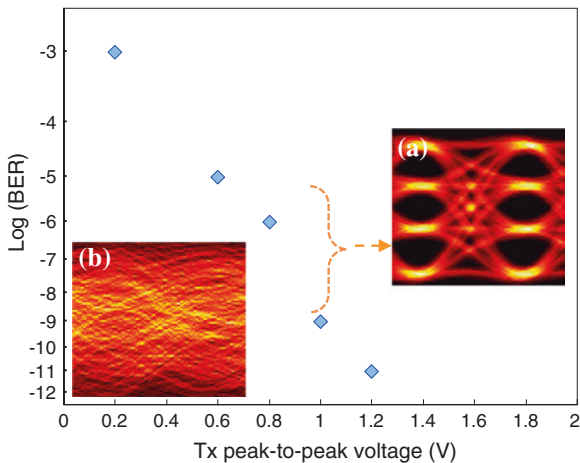


Fig. 4.2 Generation of the 4-ASK modulation format

Fig. 4.3 BER performance against different peak-to-peak driving voltages. Insets: Measured eye-diagrams of **a** with and **b** without the FIR digital filtering



closed. This is because the data rate of the applied signal was much beyond the direct modulation bandwidth of the white-light phosphor-based LED. No BER can be measured in this case.

Advanced modulation, such as orthogonal frequency division multiplexing (OFDM) provides high spectral efficiency; hence allowing high data rate (>1 Gb/s) transmission in the bandwidth limited LED communication. Figure 4.4 shows the logic flow diagram of the OFDM LED VLC described in [24]. At the Tx, the pseudo-random binary sequence (PRBS) data was first mapped to quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM). Then the data was serial-to-parallel converted, render to  $N - 1$  symbol streams and modulate  $N - 1$  OFDM subcarriers (note that the DC subcarrier was un-modulated). To produce real-value signal for the inverse fast Fourier transform (IFFT), conjugate symmetry was needed. By performing the conjugate symmetry conversion, the  $X_0 = X_N = 0$ ;  $X^*_n = X_{2N-n}$ , where  $X$  and  $X^*$  were the input symbol and its conjugate symmetry respectively. Hence at the output,  $2N$  OFDM symbols were obtained. After the IFFT, a section of the  $2N$  symbols were inserted for the cyclic prefix (CP). After the CP insertion, the OFDM symbols were re-sampled two times. Then the OFDM data was applied to the LED via a digital-to-analog converter (DAC), which was an arbitrary waveform generator (AWG). The received VLC signal was captured by a real-time oscilloscope (RTO), which was an analog-to-digital converter (ADC). The digital signal was then down-sampled, CP removed and FFT. The channel estimation was implemented at the Rx side to perform the one-tap equalization for enhancing the channel capacity. After the channel estimation and equalization, the QAM de-mapping and decoding were performed. Then the average signal-to-noise ratio (SNR) was calculated by averaging the SNRs of all the subcarriers, and the BER was calculated based on the average SNR [24].

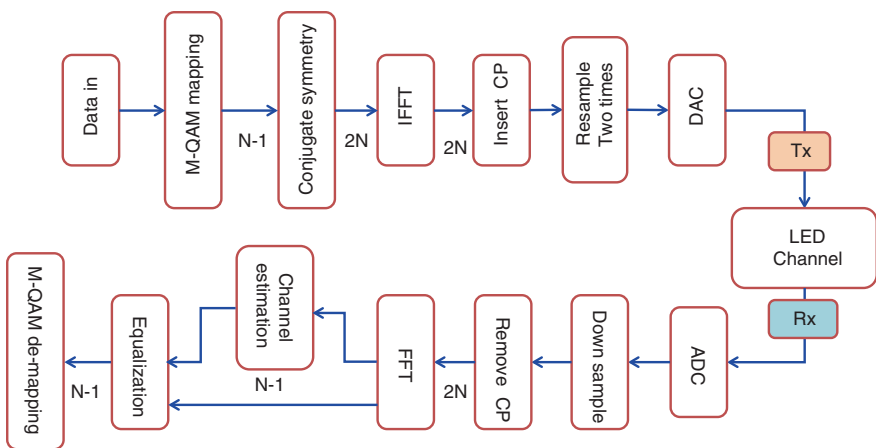


Fig. 4.4 Flow diagram of the LED VLC using OFDM

The OFDM system needs precise synchronization for the IFFT/FFT operations. Besides, channel estimation is also needed to provide parameters for signal equalization enhancing the transmission performance. One method to achieve synchronization and equalization is to use training symbol. The idea of training symbol is to use a known data to estimate the channel response. However, one or more OFDM symbol is used to carry the training symbol; hence, the effective capacity of the system may be reduced. Another scheme to achieve equalization is using pilot-tone. Since the pilot-tone is embedded into some or all OFDM symbols, the particular OFDM symbol carrying the training sequence can be used for carrying the payload data. As the channel response (both amplitude and phase) of the VLC system is relatively flat and continuous, channel estimate using pilot-tone could be effective. In the OFDM system, CP is copied from the end of the OFDM symbol to the front for reducing the inter-symbol interference (ISI). It can be assumed that the front part of OFDM symbol is still similar to the end after the channel. Then, auto-correction can be used to create a period relationship for synchronization.

Figure 4.5 shows the experimental results for using adaptive bit-loading for different OFDM subcarriers in a RGB LED. In adaptive bit-loading, the number of bits that can be transmitted in each subcarrier is determined by the SNR of that subcarrier. As SNR varies from user to user on the same subcarrier and also changes over time, channel utilization and data rate can be improved by using adaptive bit-loading. In the demonstration, RGB LED with data rate  $\sim 1$  GHz can be achieved.

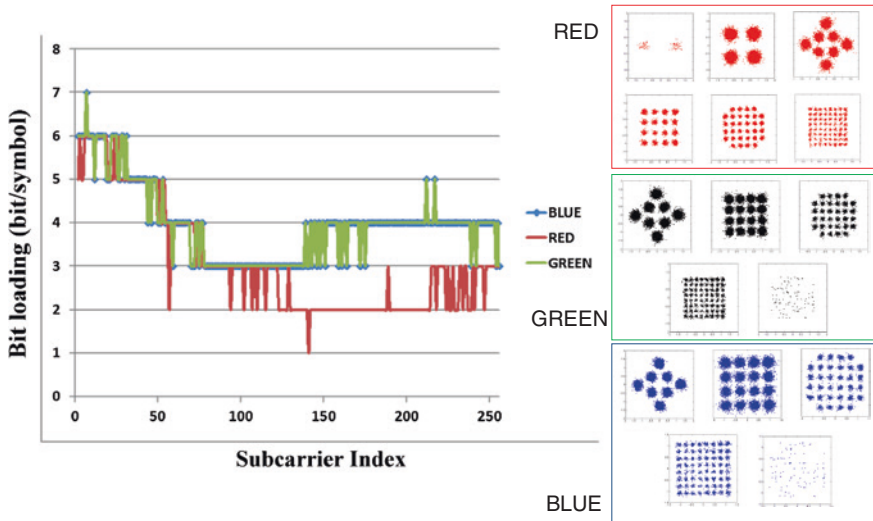


Fig. 4.5 Adaptive bit-loading for different OFDM subcarriers in a RGB LED. Insets Constellation diagrams for the red, green and blue LEDs

### 4.2.2 Mitigation of Optical Background Noises

Background optical noises can affect the performance of the VLC significantly. Scenarios may happen when the LED lamps and conventional fluorescent lamps or AC-LED lamps coexist in the same place. Chow et al. [24] reported the experimental results of the background noise mitigation by using white-light LED OFDM VLC. 64 OFDM subcarriers were used (each subcarrier was in 4-QAM). The transmission data rate was 12 Mb/s, and the bandwidth was 6.25 MHz. The OFDM carrier spacing was 97.66 kHz. A fluorescent lamp was used to produce different optical interference noise powers. The spectral characteristics of the fluorescent lamp noise were shown in Fig. 4.6. The gas discharge lamps, like the fluorescent lamps, needed a ballast to operate. The ballast converted the main supply 60 Hz frequency to higher frequencies for efficient lighting. The fluorescent lamp had a dominant frequency tone at 90 kHz, and harmonic tones at 180, 270 kHz.

Figure 4.7a, b show the SNR of each OFDM subcarrier at the data rate of 12 Mb/s. Different fluorescent noise powers (5 and 15 dB) were introduced in the VLC link. These noise powers were defined as the ratio of fluorescent power to the Rx thermal noise. The Rx thermal noise power was measured when all light sources (LED and fluorescent light) were switched off. When the fluorescent noises were added, the SNR at lower frequency OFDM subcarriers were affected, since the dominate tone of the fluorescent noise was at 90 kHz. It corrupted the

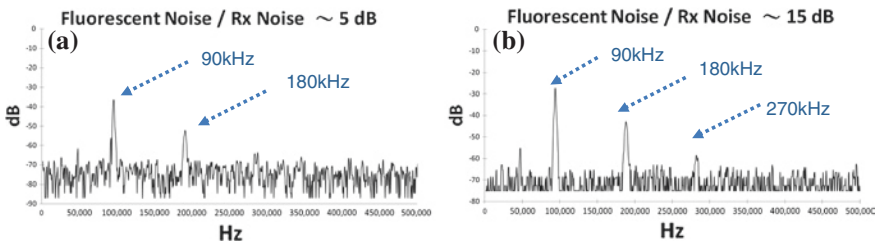


Fig. 4.6 RF spectra of the fluorescent light at noise powers of **a** 5 dB, **b** 15 dB

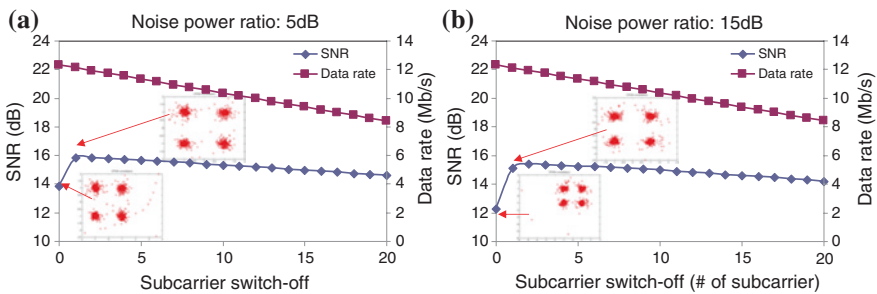
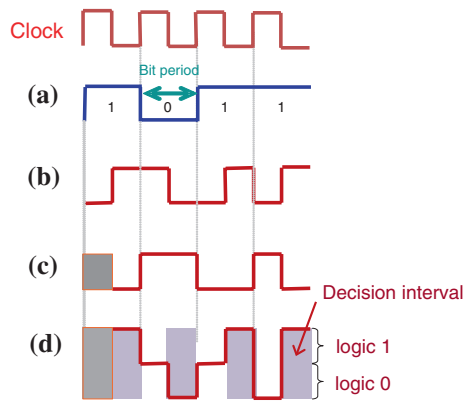


Fig. 4.7 SNR when different OFDM subcarriers were switched-off when the fluorescent noise was **a** 5 dB, and **b** 15 dB

lower frequency OFDM subcarriers. The fluorescent noise can be mitigated by dynamically control the number of OFDM subcarriers. This can be easily achieved in the Tx by not applying the data onto these subcarriers, or neglecting these subcarriers at the Rx. Since the first OFDM subcarrier was at 97.66 kHz, by switching off the first subcarrier, the VLC link can be restored. However, the total capacity was decreased from 12.3 to 12.1 Mb/s.

Besides using OFDM, modulation format such as Manchester coding can also mitigate the optical background noise. Chow et al. [25] demonstrated using Manchester coding to mitigate the optical noise. Another advantage of the Manchester coding is that it can provide signal synchronization and enhance the clock recovery. Figure 4.8 illustrates the encoding and decoding of the Manchester signal. In Manchester coded signal as shown in Fig. 4.8b, the transition from low-to-high represents logic “1”, and the transition from high-to-low represents logic “0”. The Manchester signal was generated by using exclusive-or (XOR) operation of the original non-return-to-zero (NRZ) data and the clock. At the Rx, the Manchester signal was power divided (Fig. 4.8b), one part was half-bit delayed as shown in Fig. 4.8c. Then, one part subtracted the other part using different amplifier for decoding. Finally logic decision can be made at the time interval as shown in Fig. 4.8d. By comparing the original NRZ signal shown in Fig. 4.8a, it illustrates that the received signal can be correctly decoded.

Conventional NRZ coding VLC was compared with the Manchester coding VLC, and the signals were experimentally evaluated using Q-factors under different “fluorescent noise power/thermal noise power” ratios in [25]. It is observed from Fig. 4.9 that Manchester coding can significantly mitigate the noise. The Manchester coded signal showed error-free optical wireless communication ( $Q > 6$ ) in all the measurements, while the transmission of the NRZ coded signal produced high error even at low noise level. The insets show the corresponding eye-diagrams. The eye-shape of the received Manchester signal had a half-bit



**Fig. 4.8** Schematic bit-pattern: **a** NRZ signal, **b** Manchester signal, and **c** half-bit delayed Manchester signal and **d** decoded Manchester signal



period of the NRZ. This was due to the received Manchester signal subtracted its half-bit delayed signal in the demodulation.

The explanation of the noise mitigation principle of the Manchester signal was as follow. Figure 4.10a, b show the simulated power spectra of the NRZ coding and Manchester coding, both with the optical noise at frequency of  $0.08/\tau$ . Due to the high spectral overlap of the optical noise with the power spectrum of the NRZ signal, high signal distortion was observed in NRZ case. In the Manchester

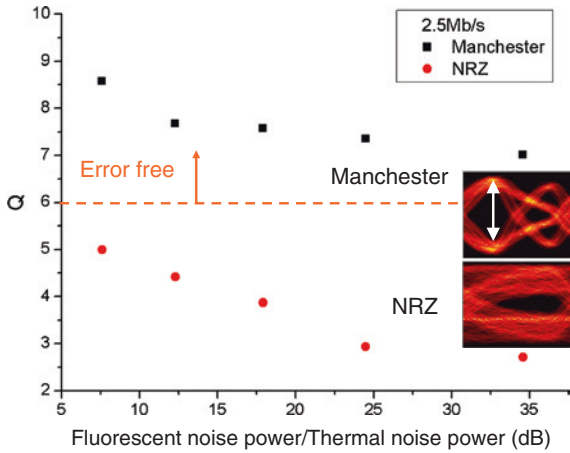


Fig. 4.9 BER of NRZ and Manchester coded signal

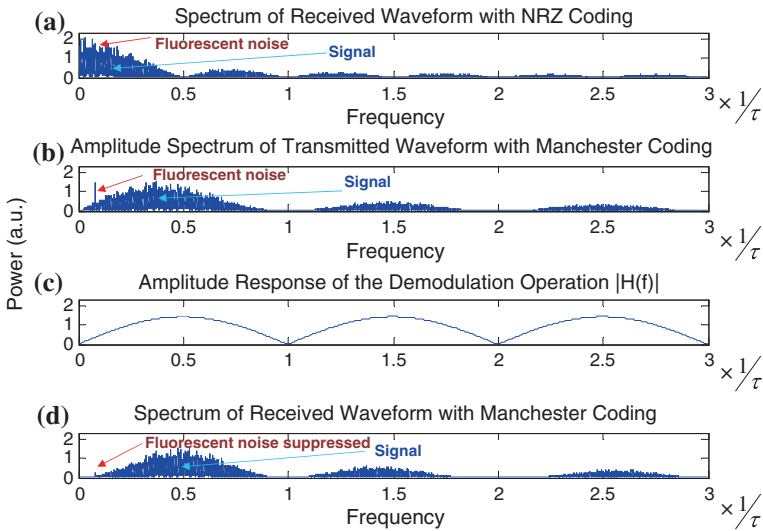


Fig. 4.10 Simulated power spectra of the a received NRZ signal, b received Manchester signal, c transfer function of decoding process and d decoded Manchester signal

decoding process, the received signal went through the decoding, which was equivalent to passing through a periodic band-pass filter as shown in Fig. 4.10c. As a result, the optical noise can be effectively suppressed as shown in Fig. 4.10d.

### 4.2.3 Bi-Directional Transmission

Since VLC is basically a broadcast transmission, providing an uplink path in VLC is challenging. Komine et al. [26] described an uplink VLC path by using modulated retro-reflecting link; however the available modulators are generally low speed and costly. Besides, the location of the Rx needs further study. Hou and O'Brien [27] described using radio-frequency (RF) to provide the uplink path; however it cannot be used in some RF restricted areas. Liu et al. [28] demonstrated a bi-directional transmission link using white-light LED VLC in both downlink and uplink paths. Time-division-duplex (TDD) was implemented to significantly eliminate the reflection interference in VLC.

Figure 4.11 shows the experimental setup of TDD VLC system reported in [28]. The downlink and uplink data were generated by function generator (FG1 and FG2) respectively. The uplink signal from FG2 was applied to a single white-light LED, while the downlink signal from FG1 was applied to a  $5 \times 8$  LED array with a DC bias of 10 V (the 40-LED array had a maximum driving voltage of 12 V). Both the downlink and uplink signals were modulated using NRZ for-mat. To study the reflection interference, two mirrors were placed at about 25 cm away from the LEDs as shown in Fig. 4.11.

Figure 4.12 shows the uplink path analysis in the bi-directional TDD VLC experiment [28]. It shows the SNR of uplink signal under different interference power ratios with and without using the TDD. The interference power ratio was defined as the power ratio of the interference signal to the uplink signal. By tuning the mirror angles, the interference powers were adjusted accordingly. The SNR degraded when the interference power increased without using the TDD mode. By using the TDD mode, the uplink signal was nearly not affected by the reflected

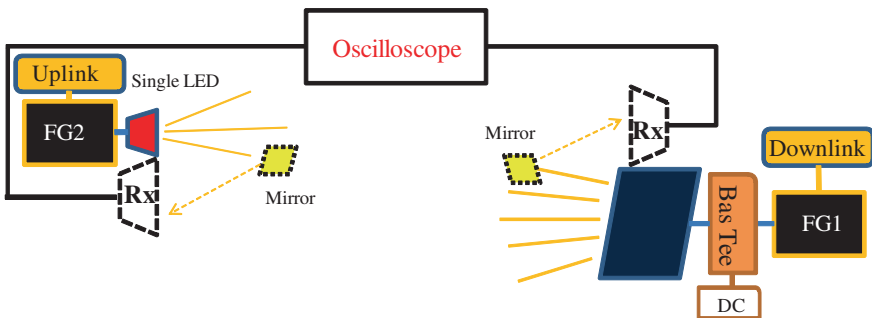


Fig. 4.11 Experimental setup for the TDD VLC system

interference signal, showing the proposed scheme can significantly eliminate the reflection interference even at high reflection power.

Besides using visible light to provide the uplink path in the bi-directional communication, infrared (IR) can also be used to provide the uplink path. Figure 4.13 shows the bidirectional VLC system together with its corresponding module design demonstrated by Industrial Technology Research Institute (ITRI) and

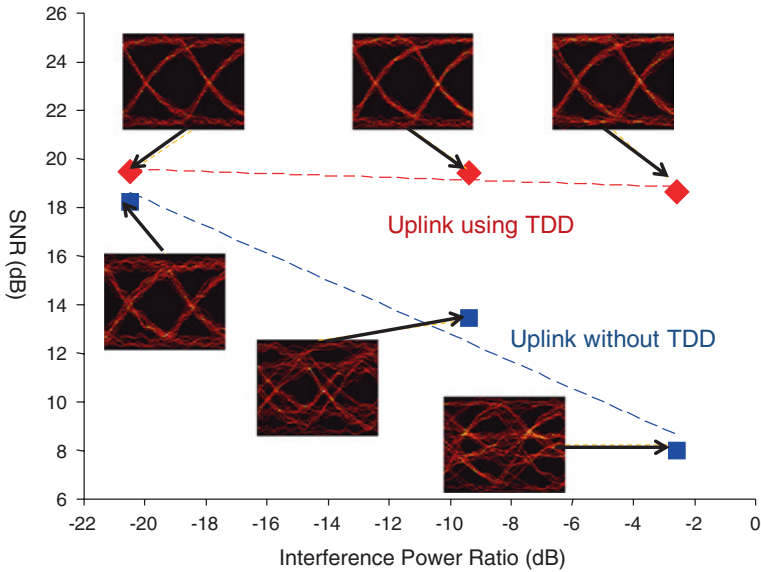


Fig. 4.12 SNR against different interference power ratios with and without using TDD

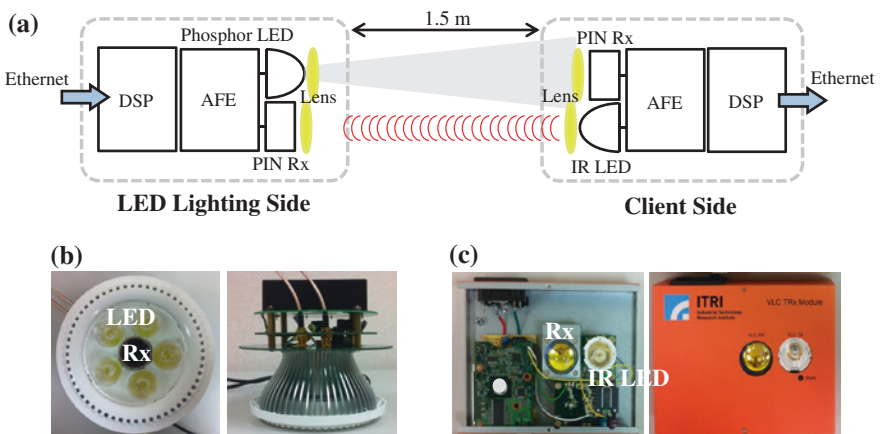


Fig. 4.13 a Bi-directional LED VLC system using IR uplink, b LED lighting and Tx side and c Rx client side

National Chiao Tung University (NCTU). In LED lighting side, phosphor based white-light LEDs served as the Tx for lighting and VLC simultaneously. In client side, an 850 nm IR LED was used as Tx for uplink traffic. Two corresponding optical PIN Rx's with 50 MHz bandwidth were placed in lighting and client sides. There were two main designs for the LED lighting and client sides. One was the analog front end (AFE), and the other was digital signal processing (DSP), as illustrated in Fig. 4.13. In AFE part, it combined the DC power and modulation data and received the optical signal. Pre-equalization technology was performed in the AFE part. In the DSP part, real-time OFDM-based DSP chip was used. A real-time video demonstration was also performed, as shown in Fig. 4.14.

### 4.2.4 Using AC-LED for VLC

It is more energy-efficient to use AC-LED instead of DC-LED for lighting, and many AC-LED technologies have been developed. It is highly desirable using AC-LED for the VLC. One main challenge for the AC-LED VLC is the synchronization issue for modulating the data during the turn-on period of the AC-LED. A microcontroller was used in previous research of using AC-LED for VLC [29, 30]. Liu et al. [31] demonstrated an AC-LED based system, which was designed using



Fig. 4.14 Real-time bi-directional LED VLC system using IR uplink

a synchronized signal modulation with clock recovery and bias-tee circuits. It was verified to support 5 ms time slot without distortion caused by the threshold voltage limitation of LED.

Figure 4.15 shows the experimental setup for AC-LED based system in [31]. The 110 Vrms with a frequency of 60 Hz was provided from power outlet and converted to 9 Vrms by transformer (optional). A 60 Hz square wave synchronized to the AC power bias signal was generated by the clock recovery circuit, with duty cycle of ~50 %. Then, the signal was used to synchronize the AWG. The sinusoidal wave was rectified to have positive voltage only at the output of the full-wave rectifier. Finally, the bias-tee circuit combined the signals from the AWG and the full-wave rectifier for driving the LEDs.

The received waveform of the AC-LED VLC system is shown in Fig. 4.16a using QPSK formats. The rectified AC power bias signal was modulated by the

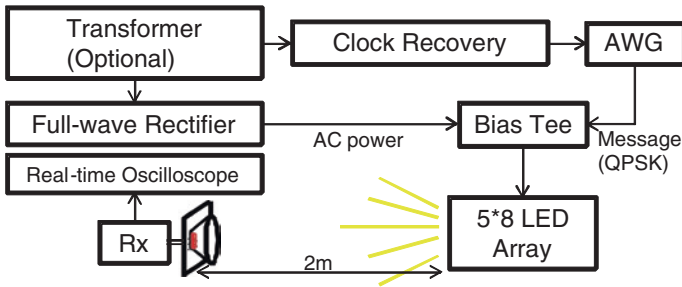


Fig. 4.15 Experimental setup of the AC-LED biased communication system

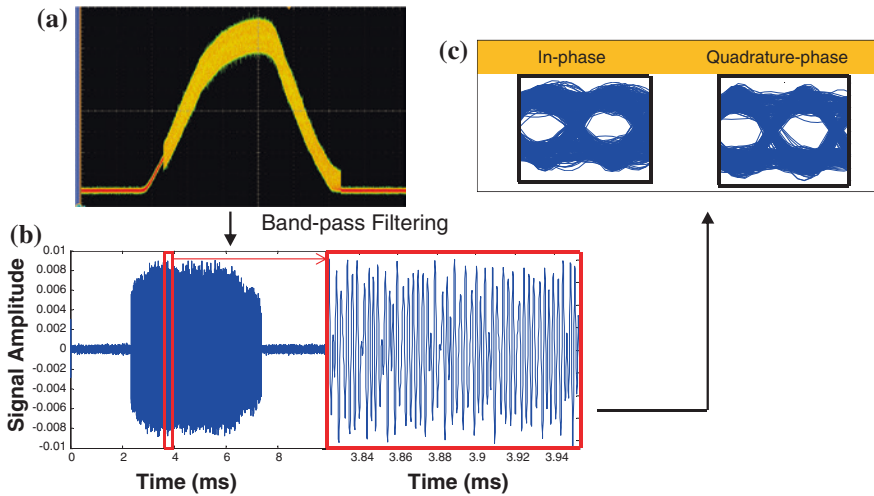


Fig. 4.16 a Received waveform of the AC-LED VLC system, b filtered waveform and c the corresponding eye-diagrams

QPSK data signal. Then, by using a band-pass filter, the received signals can further be processed to remove the 60 Hz AC power signal. The filtered waveform and the eye-diagram were shown in Fig. 4.16a, b, respectively.

Recently, power line communication (PLC) has emerged as a promising wired communication for in-home communication using already installed mains power cables. It is convenient over traditional Ethernet since no additional cables are needed. Researchers are planning to integrate the PLC and the VLC [32]. Hence, the further integration of PLC and AC-LED could increase the network flexibility and scalability.

### 4.3 Summary

VLC is a kind of optical communication using visible wavelength of the electromagnetic spectrum from 380 to 780 nm. VLC using LED lamps has attracted much attention recently for providing secure and high speed data transmissions. We have discussed the worldwide VLC activities. We also discussed different technical aspects of the VLC. These include enhancing the transmission data rate of VLC, mitigation of the optical background noises, achieving a bi-directional transmission, and using AC-LED for VLC.

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