Research Highlights

Digital Signal Processing for Light Emitting Diode Based Visible Light Communication

C. W. Chow¹, C. H. Yeh², Y. Liu³, and Y. F. Liu¹

Abstract—The realization of enhanced efficiency light emitting diodes (LED) and the trend to lower costs of LED lighting systems will facilitate their wider deployment in many applications. LED lighting system with the value-added functionality of optical wireless communication enables the deployment of a communication system with very little extra cost. Visible light communication (VLC) provides the merits of secure information exchange, harmlessness to human body, and excellent applicability in some radio-frequency (RF) restricted areas. In this work, we review some recent advances in VLC. We discuss the challenges faced by the VLC and some possible solutions. We discuss and show that using digital signal processing (DSP) can significantly enhance the VLC performance.

I. Introduction

The combination of power efficiency improvements and cost reduction in light emitting diodes (LEDs) has expanded the deployment of LED to a variety of applications, such as traffic light, automobile lights, display backlights and as well both in-door and out-door general lighting. LED has the advantages of high power efficiency, rigid, compact size, long lifetime, and easy integration in different products. In the near future, LED will gradually replace traditional incandescent and fluorescent lamps for general lighting applications. When compared with the traditional incandescent light, LED consumes less than half the energy at the same lumens output. Recently, the power efficiency of LED has surpassed that of fluorescent lamps, making it one of the most energy efficient lighting sources in the market. The major LED suppliers (Cree, Nichia, Osram, Lumileds, etc…) are competing to improve their LED output performances. For example, Cree reported achieving a power efficacy of 254 lm/W under standard room temperature testing at 350 mA in April 2012 [1]. Besides, LED is generally regarded as an eco-light source. It can reduce the emission of global warming gases since less electricity is consumed. It is estimated an installation of more than 20,000 street lights in Chongqing, China, can produce annual cost savings in maintenance and electricity of more than USD 3 million and 17.6 million kWh [2].

LED has unique characteristics which make possible new applications not possible with other kinds of light sources. The LED can be modulated at higher speeds (~MHz) than the traditional lighting sources, such as fluorescent lamps. Hence, it is possible to use the LED lighting for visible light communication (VLC) for in-building optical wireless networks. VLC transmission power comes effectively free as it is already used for illumination. The development of LED-based VLC solution is thus very attractive.

VLC can provide many transmission advantages. Being an optical wireless technology, VLC can provide a cable free environment. Fig. 1 shows the wireless smart home, where the triple-play services (TV, phone, Internet) can be provided using VLC. It can be a secure link between mobile devices, since the light beam is visible, users can securely limit the coverage of data broadcast by controlling the area of illumination, unlike WiFi signals which may leak out to adjacent rooms or buildings. In addition as the optical power does not penetrate through walls, there is no interference with users in other rooms. VLC is the only solution for wireless network in some areas where radio frequency (RF) communication is prohibited. It can be used in hospital or in an aircraft for example without producing electromagnetic interference.

The paper is organized as follow. In Section II, we will briefly mention some recent developments in VLC from around the world. In Section III, we will discuss the challenges faced by the VLC. Then in Section IV, we will discuss our recent work on the use of digital signal processing (DSP) to enhance VLC performance. Finally, a conclusion will be provided in Section V.

II. Worldwide VLC Activities

Since more and more LEDs are deployed to perform the primary function of lighting, the value-added communication function can be realized at very little extra cost. Recently, VLC is a rapidly growing research topic. The Japan-based Visible Light Communication Consortium (VLCC) [3] was formed in 2002 to

1 Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, (Taiwan)
2 Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), (Taiwan)
3 Hong Kong Productivity Council (HKPC), (Hong Kong)
publicize VLC. In the United States, the Center for Ubiquitous Communication by Light (UC-Light) funded by the University of California (UC) system has been established [4]. It is to enable wireless communications by embedding signals into the light emitted by next-generation LED in systems for illumination, traffic control, advertising, and other purposes. Besides, the Smart Lighting Engineering Research Center [5] has been established to develop new technologies of optical wireless access to the internet with energy savings. In Europe, the OMEGA Project [6] funded by the European Commission under the Seventh Research Framework Programme (FP7) has been started in 2008. Its aim is to develop a home area network capable of delivering high-bandwidth services and content at a transmission speed of one Gigabit per second. It consists of 20 European partners from industry and academia. An IEEE standard (IEEE 802.15.7—Short-Range Wireless Optical Communication Using Visible Light) has been finalized in 2011 [7], enhancing the prospects for commercializing the VLC technology. It covers both the physical layer (PHY) air interface and the medium-access control (MAC). The MAC layer supports three multiple access topologies; peer-to-peer, star configuration and broadcast mode, while the PHY layer is divided into three types: PHY I (designed for outdoor, data rates: 11.67–266.6 kb/s), PHY II (designed for indoor, data rates: 1.25–96 Mb/s) and PHY III (designed for applications where RGB source and receiver (Rx) are used, data rates: 12–96 Mb/s).

III. Challenges of VLC

A. Data Rate

There are two major types of device structures for white LED for use in general lighting. The first type consists of a blue LED chip with a phosphor layer coated on top of it. When electric current is applied to the LED chip, blue light is emitted and part of it is absorbed by the phosphor to generate second color—yellow light. The combination of blue and yellow lights results in white light. The other type of LED is fabricated by mixing light from the three primary colored chips (RGB). Three chips emit each color simultaneously and at the output white light is produced. The phosphor white LED has the advantage of low cost. However, the nature of phosphor light conversion makes it unsuitable for high speed direct modulation because the response time of phosphor is much lower than the LED chip, and the direct modulation speed is usually limited to a few MHz. This disadvantage has motivated some research to improve the direct modulation speed of the white LED.

One of the approaches to improve the direct modulation speed is to use a blue optical filter at the Rx to remove the slow response yellow light. However, this introduces a power penalty as energy in the visible optical spectrum except the blue are blocked and hence limits the VLC transmission distances. Pre-equalization and/or post-equalization of the LED can be used. 40 Mb/s and 80 Mb/s pre-equalized on-off-keying (OOK) transmissions without and with using optical blue filter; and 100 Mb/s post-equalized OOK have been reported in ref. [8], [9] and [10] respectively. By optimizing the electronic circuitry, a VLC link at 125 Mb/s at bit-error rate (BER) below $2 \times 10^{-3}$ can be achieved [11]. Instead of using PIN Rx, avalanche photodiode (APD) can enhance the data rate to 230 Mb/s [12].

Another approach to increase the modulation data rate is to employ advanced modulation formats. Orthogonal frequency division multiplexing (OFDM) (a form of discrete multi-tone (DMT)) can be used to improve the spectral efficiency [13]. By implementing the bit and power loading techniques of the subcarriers of the OFDM signal, 231 Mb/s (using PIN Rx) and 513 Mb/s (using APD) can be achieved in ref. [14] and [15] respectively. 803 Mb/s data rate VLC transmission has been demonstrated using RGB LEDs, which enable the use of wavelength division multiplexing (WDM) to carry different data in different color LEDs [16]. Besides using WDM, parallel data transmission in multiple LEDs using multi-input multi-output (MIMO) techniques can also increase the data rate of the VLC link [17].

B. Duplex Transmission

VLC is a broadcast communication, and providing an upstream communication channel is challenging. Several approaches have been considered, such as using the infra-red (IR) or flashlight LED in the portable device for the upstream communication. A retro-reflector can be used to modulate the incident light generating the upstream signal [18]. The use of radio-frequency (RF) to provide an upstream channel has also been considered. At present there is no concrete conclusion as to
which solution is the best, and further work is required to develop potential techniques and compare alternatives.

C. Dimming Control

Another challenge in VLC is how to communicate when the lights are “off”. If the lights are usually “on”, VLC transmission power comes free as it is already used for the illumination. However during daytime, people tend to switch off the room lights. In order to maintain the communication link, the LED should be “on”. In this case, similar to RF wireless communications, the power consumed for the data transmission is not free. One technique that may be used is to reduce the LED brightness to a level low enough so that people will accept that the light is “off” [19].

IV. Digital Signal Processing for the VLC

White-light VLC system using phosphor-based LED is cost-effective when compared with the RGB white-light LED; however the slow response of the phosphor limits the direct modulation speed. Fig. 2 shows frequency response of a commercially available phosphor-based LED for lighting (Cree, Xlamp XR-E LED), showing a 3-dB bandwidth is 1.28 MHz. Hence the transmission data rate will be limited to about 1 Mb/s if the equalization scheme or advanced modulation is not used.

First of all, we discuss using a simple digital post-equalization finite impulse response (FIR) equalizer to enhance the direct modulation speed. No optical blue filter is used. The experimental result shows about 10 times enhancement of the direct modulation speed of white-light LED VLC system. When compared with the previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor [20], this scheme shows an improvement in signal quality and transmission distance, and a 10 Mb/s error-free (BER < 10^-9) transmission over a distance of 1 m was demonstrated.

A simulation using the simple FIR equalizer to correct the VLC channel effect was performed. The electrical-to-optical-to-electrical (E-O-E) channel of the VLC system can be modeled as a first-order RC low-pass circuit as shown in Fig. 3(a). The corresponding impulse response (time domain) of an analogue low-pass RC system can be written as:

$$H_t(t) = \exp\left(-\frac{t}{RC}\right)$$

Then the designed equalizer can be modeled as a first-order high-pass circuit to compensate the channel response as shown in Fig. 3(b). The transfer function (in frequency domain) of this equalizer can be written as follow:

$$H_2(\omega) = \frac{R_2}{j\omega CR_1 + 1 + R_2}$$

In Eq. (1), the 1/RC is set to 1.28 MHz, which is the measured 3-dB bandwidth of the system (as shown in Fig. 2). Eq. (2) was used to model the equalizer, and suitable parameters are selected to compensate the EOE response of the VLC system.

Experiments on VLC have been performed as shown in Fig. 4(a), with a photograph of the experimental setup as shown in Fig. 4(b). A 10 Mb/s, pseudorandom binary sequence (PRBS) 2^10-1 data was applied to a single phosphor-based LED (Cree, Xlamp XR-E LED via an arbitrary waveform generator (AWG). The bandwidth and the resolution of the AWG were 20 MHz and 14-bits respectively. The sampling rate is 50 MSa/s. The LED was DC-biased at 2V with peak-to-peak signal modulation voltage from 0.1 to 0.5 V. A lens was used to enhance directivity, and the free-space transmission distance is 1 m. The visible signal is detected by a silicon-based PIN Rx, amplified, and finally captured by a real-time oscilloscope (RTO). The PIN Rx has the detection wavelength range of 350–1100 nm with responsivity of 0.65 A/W and active area of 13 mm². It had a bandwidth of 17 MHz and the root mean square (rms) noise of 530 μV. The bandwidth of the RTO is 100 MHz, with vertical resolution of 9-bit and sample rate of 1.25 GSa/s. The data is analyzed using 1700 bits.

![Figure 4](image)

Figure 4. (a) VLC experimental setup and (b) photograph of the experiment.

![Figure 5](image)

Figure 5. BER measured of the VLC system using the FIR equalizer. Insets: eye-diagram (a) without the digital FIR equalizer and (b) with the digital FIR equalizer.
BER measurements were performed by using the measured Q factors of the different eye-diagrams obtained at different AC peak-to-peak signal voltages. For example the measured eye at 10 Mb/s is shown in Fig. 5. Inset of Fig. 5(a) shows the measured eye-diagram without using the proposed FIR equalizer. The eye is completely closed due to the inter-symbol interference (ISI) generated by the limited modulation bandwidth of the LED. The BER cannot be analyzed in this case. Inset of Fig. 5(b) shows the FIR equalized eye-diagram, with a significantly improved eye opening. When the peak-to-peak driving voltage is $V_{pp} = 0.5$ V, an error-free BER $< 10^{-9}$ can be achieved. When compared with our previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor [20], the proposed DSP scheme shows an improvement in transmission distance (from 10 cm to 1 m) and in signal quality (at BER of $10^{-9}$, peak-to-peak driving voltage is reduced from 1 V to 0.5 V), since the digital FIR equalizer allows a more precise and flexible control of the equalizer parameters.

Then, we further enhance the VLC data rate by using quaternary-amplitude-shift-keying (4-ASK) modulation and digital filtering [21]. A 20 times enhancement of the direct modulation speed of white-light LED VLC system is demonstrated by using digital filter only and without using optical blue filter. A digital filter and square root raised cosine (SRRC) filter are used for signal equalization. Error-free transmission over a distance of 1 m was demonstrated.

Fig. 6 shows the signal flow of 4-ASK modulation generation using DSP. First, the binary sequence is mapped to 4-ASK symbol which contains 4 different amplitude levels to represent 2 bit/symbol. The up-sampling increases the sampling rate by inserting zeros between the original sample points. The digital FIR equalizer creates a frequency domain compensation for the system channel response. The Tx, VLC channel and the Rx are the same as discussed in previous experiment. A SRRC filter (rolloff factor 0.25) is used after Rx. The adaptation process of adaptively-controlled FIR equalizer is to transmit a known series of training symbols, and the received pattern is analyzed. The result is used for adjusting the FIR equalizer coefficients in the next transmission. The estimation is based on FFT (Fast Fourier transform) to estimate the zero forcing equalizer (ZFE) which is the updated FIR coefficients to invert the channel response. The FIR filter has 13-taps denoted as $h[i]$, with the initial setting of $h[0] = 3.5$, $h[1] = 3.5$, $h[2] = -2.5$, $h[3] = -2.5$, and otherwise $h$ is zero. After 10 iterations, the filter coefficients converged to fixed numbers and the system is stabilized (condition of matched filtering). The optical 4-ASK symbol is shaped with the filter response of FIR equalizer and the transfer function of the physical electrical-optical-electrical (E-O-E) channel. The SRRC filter at the Rx then enhances the SNR of the received signal. The mathematical expression for SRRC filters are described in [22].

BER measurements were performed by using the measured Q factors of the eye-diagrams at different AC peak-to-peak signal voltages, with the measured 20 Mb/s eye-diagrams as shown in Fig. 7. Inset of Fig. 7(a) shows the measured eye-diagram without using the proposed scheme. The eye is completely closed since the ISI and BER cannot be analyzed in this case. A clear and wide open 4-ASK eye-diagram can be obtained by using the proposed scheme, as shown in Fig. 7(b).
When the peak-to-peak driving voltage is \( \geq 1 \) V, an error-free BER \( < 10^{-9} \) can be achieved.

V. Conclusion
In summary we highlighted some of the VLC activities from around the world. We also discussed the advantages and challenges of the VLC system, together with some possible solutions. Using DSP could be a good choice to enhance the VLC performance. We proposed and demonstrated using a simple digital post-equalization FIR equalizer to improve the bandwidth limitation of LED VLC channel. No optical blue filter was used. The experimental results showed \textasciitilde 10 times enhancement of the direct modulation speed of VLC system using OOK modulation format. We also proposed and experimentally demonstrated the 4-ASK modulation with FIR digital equalizer to further enhance the direct modulation speed of white-light LED VLC system to 20 times.

Acknowledgments
This work was financially supported by the National Science Council, Taiwan, R.O.C., under Contract NSC-101-2628-E-009-007-MY3, NSC-100-2221-E-009-088-MY3 and ITRI industrial-academic project. We would like to thank Prof. Hon Tsang of the Department of Electronic Engineering, The Chinese University of Hong Kong for useful discussion.

References
5. Smart Lighting ERC, www.smartlighting.rpi.edu