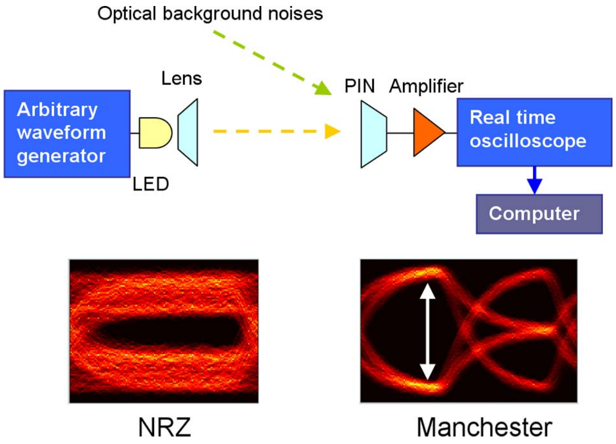
IEEE Photonics Journal
An IEEE Photonics Society Publication

Mitigation of Optical Background Noise in Light-Emitting Diode (LED) Optical Wireless Communication Systems

Volume 5, Number 1, February 2013

C. W. Chow
C. H. Yeh
Y. F. Liu
P. Y. Huang



DOI: 10.1109/JPHOT.2013.2238618

Mitigation of Optical Background Noise in Light-Emitting Diode (LED) Optical Wireless Communication Systems

C. W. Chow,[1] **C. H. Yeh,**[2,3] **Y. F. Liu,**[1] **and P. Y. Huang**[1]

[1]Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University,
Hsinchu 30010, Taiwan
[2]Information and Communications Research Laboratories, Industrial Technology Research Institute
(ITRI), Hsinchu 31040, Taiwan
[3]Graduate Institute of Applied Science and Engineering, Fu Jen Catholic University,
New Taipei 24205, Taiwan

DOI: 10.1109/JPHOT.2013.2238618
1943-0655/$31.00 ©2013 IEEE

Manuscript received December 1, 2012; revised December 31, 2012; accepted January 4, 2013. Date of publication January 11, 2013; date of current version February 6, 2013. This work was supported in part by the National Science Council, Taiwan, under Contracts NSC-101-2628-E-009-007-MY3 and NSC-100-2221-E-009-088-MY3 and in part by ITRI industrial–academic project. Corresponding author: C. W. Chow (e-mail: cwchow@faculty.nctu.edu.tw).

Abstract: One challenge faced by the in-home light-emitting diode (LED) optical wireless communication is the optical noises. Here, we first experimentally characterize the effect of optical background noise to the performance of the LED optical wireless communication channel. We demonstrate using Manchester coding for the LED to mitigate the optical noise. No adaptive monitoring, feedback, or optical filtering is required. The theoretical and numerical analysis of Manchester decoding process to mitigate the optical background noise is provided. Our experimental result shows that Manchester coding can significantly eliminate optical noise generated by the AC-LED operated at $<$ 500 kHz and fluorescent light.

Index Terms: Free-space communication, optical communications, light-emitting diode (LED), noise mitigation.

1. Introduction

Nowadays, light-emitting diodes (LEDs) have been used in many places, such as traffic lights, automobile indicators, displays, and flashlights because of the long life-time, high power efficiency, and compact size. Integrating the LED general lighting with communication can provide optical wireless communication [1]–[5] with very low extra cost. LED optical wireless communication offers many transmission advantages, such as electromagnetic interference (EMI) free, license-free, high security. There are several challenges for the practical implementation of the LED optical wireless communication. One of the challenges is the limited direct modulation speed of the white LED. Several techniques have been proposed to solve this issue, including the use of pre- or post-equalization [6], [7] or advanced modulation formats, like discrete multitone (DMT) [8].

Another challenge faced by the LED optical wireless communication is the optical noise generated by the AC-LEDs or conventional fluorescent lamps. Using adaptive filtering to reduce the optical noise interference has been proposed [9]. This scheme needs to estimate the channel characteristics and the interference signals. It then uses a linear prediction coefficient technique to equalize the received signal. However, continuous adaptive monitoring and feedback are required.

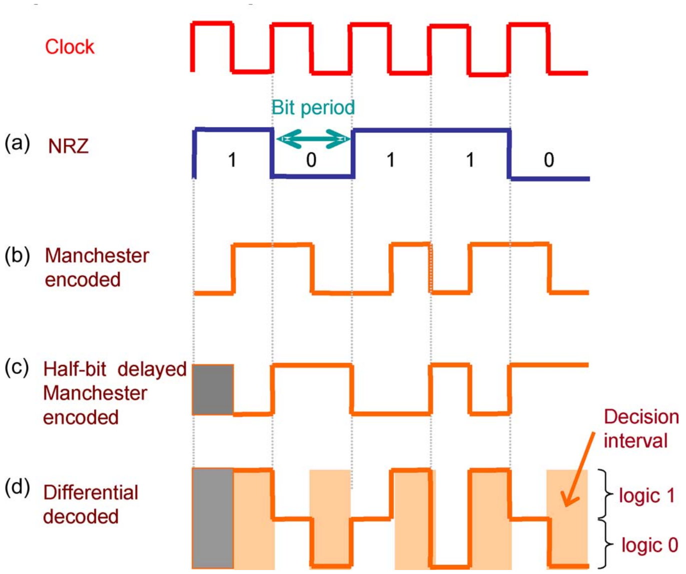


Fig. 1. Schematic bit pattern. (a) NRZ signal, (b) Manchester signal, (c) half-bit delayed Manchester signal, and (d) decoded Manchester signal.

Wavelength filtering to reduce the optical interference has been proposed [10]; however, red–green–blue (RGB) LED and optimized planning of illumination coverage are required.

In this paper, we propose and demonstrate using Manchester coding for the LED to mitigate the optical noise. No adaptive monitoring, feedback, or optical filtering is required. Other advantage of the Manchester coding is that it can provide signal synchronization and enhance the clock recovery. Further experiments are carried out to evaluate the performance of Manchester-coded optical wireless communication signal using different noise frequencies, and the experiment results show that Manchester coding performs better than the conventional non-return-to-zero (NRZ) when the optical noise frequency is $<$ 500 kHz.

2. Principle

This section will briefly discuss the encoding and decoding of the Manchester signal. Fig. 1 shows the schematic bit pattern for the Manchester coding and decoding. In Manchester-coded signal as shown in Fig. 1(b), the signal transition from low to high represents logic “1,” while the signal transition from high to low represents logic “0.” As shown in Fig. 1, the Manchester signal can be generated by using exclusive-or (XOR) operation of the original NRZ data (blue curve in Fig. 1) and the clock (red curve in Fig. 1). This signal is applied to the LED source. At the receiver (Rx), the received Manchester signal will be power divided into two parts. One part will be half-bit delayed, as shown in Fig. 1(c). The received Manchester signal will then subtract its half-bit delayed signal using offline digital signal processing (DSP) or using commercially available different amplifier for decoding. Finally, bit-error-rate (BER) decision can be made at the time interval, as shown in Fig. 1(d), indicating that the received signal can be correctly decoded when it is compared with the original NRZ signal logic, as shown in Fig. 1(a).

3. Experiment

Fig. 2 shows the experimental setup. An arbitrary waveform generator (AWG) (Agilent 33220A) generated a pseudorandom binary sequence (PRBS) $2^{10}-1$ of NRZ and Manchester electrical signals with peak-to-peak voltage of 1 V. The bandwidth and the resolution of the AWG are 20 MHz and 14 bits, respectively. The sampling rate is 50 MSa/s. These signals were then directly applied to a LED light (Cree, XLamp XR-E LED), which was DC biased at 2 V. The DC biased was provided by the AWG. The LED has a 3-dB direct modulation bandwidth of about 1 MHz. The white light was

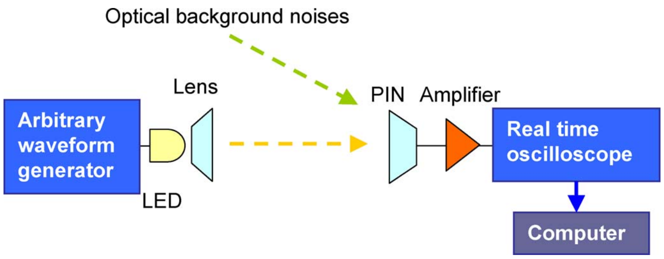


Fig. 2. LED optical wireless communication experiment setup with the effect of optical background noise.

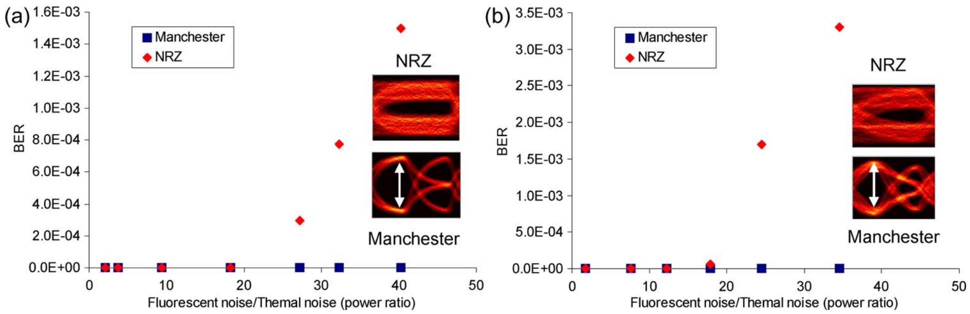


Fig. 3. BER and eye diagrams of NRZ- and Manchester-coded optical wireless communication signal at (a) 1.25 Mb/s and (b) 2.5 Mb/s.

transmitted across 1.65-m free space via a pair of focusing lens and then received by a silicon-based PIN Rx (Thorlabs PDA36A). The PIN Rx has the detection wavelength range of 350–1100 nm with responsivity of 0.65 A/W and active area of 13 mm^2. It has a bandwidth of 17 MHz and the root mean square (rms) noise of 530 μV. Then, the received electrical signal was amplified by an amplifier (Mini-Circuit ZHL-6A) and recorded by a real-time oscilloscope (Tektronix TDS2022B). The bandwidth of the real-time oscilloscope is 100 MHz, with vertical resolution of 9 bits and sample rate of 1.25 GSa/s. In the experiment of using a single LED, an illumination level of 300 lx was maintained (measured by a lux meter), and the transmission distance was about 1.65 m. According to [11], in a standard room size of 5 m $\times$ 5 m $\times$ 3 m, the LED lights were installed at a height of 2.5 m from the floor. The height of the desk was about 0.85 m. Hence, the distance between the LED lights and the user device that was put on the desk was about 1.65 m. A conventional fluorescent light from a desk lamp was purposely located near the Rx, which deteriorated the optical signal quality from LED optical wireless communication link.

4. Results and discussion

The LED optical wireless communication link using NRZ- and Manchester-coded signals were experimentally evaluated using Q-factors (linear) under different “optical noise power/thermal noise power (F/T)” ratios. BER was then calculated according to the measured *Q*-factors [12]. The thermal noise power at the Rx was measured when all light sources were switched off. The *Q* factor is defined as

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{1}$$

where μ_1 and μ_0 are the average received value for logic “1” and “0;” σ_1 and σ_0 are the noise standard deviation for logic “1” and “0,” respectively. Two data rates, i.e., 1.25 Mb/s and 2.5 Mb/s, were evaluated, and the BER against different F/T ratios are shown in Fig. 3(a) and (b), respectively. The transmitted powers for both coding schemes were the same due to the encoded data for

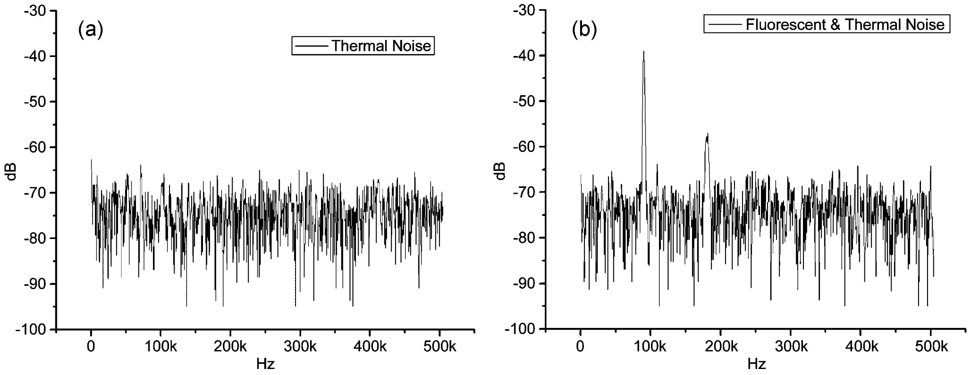


Fig. 4. Measured RF spectra of the (a) thermal noise and (b) fluorescent light and thermal noise.

both coding schemes have equal amplitude for logic “1” and logic “0” and have equal probability for the presence of logic “1” and logic “0.”

From Fig. 3(a) and (b), we can observe clearly that Manchester coding can significantly mitigate the noise. At the bit rate of 1.25 Mb/s, the Manchester-coded signal shows error-free optical wireless communication $(Q > 14)$ in all the measurements, while the transmission of the NRZ-coded optical wireless communication produces error even at low F/T of 10 dB. When the F/T increases to 40 dB, the BER of the NRZ-coded optical wireless communication is only 1.5×10^{-3}.

At the bit rate of 2.5 Mb/s (in this case, we overmodulated the LED light), hence, the Q-factors of both Manchester- and NRZ-coded signals decrease due to the intersymbol interference (ISI) generated by the limited modulation bandwidth of the LED. However, we can also observe that Manchester-coded signal performs better since the differential decoding of the Manchester signal can reduce the ISI and enhance the eye opening of the received signal. Hence, error-free operation can be achieved even the LED is over modulated by about 2.5 times. Insets in Fig. 3 show the corresponding eye diagrams, showing that the Manchester-coded optical wireless communication signal has a clearer eye diagram. In the insets in Fig. 3(a) and (b), we can observe that the eye shape of the received Manchester signal is half-bit period of the NRZ. This is due to the received Manchester signal subtracted its half-bit delayed signal in the demodulation as discussed in Fig. 1. Hence, the discussion time is at the first half-bit period of the Manchester signal, as indicated by the “white arrow” in the insets in Fig. 3(a) and (b).

The radio-frequency (RF) spectra of the “thermal noise” and “fluorescent light and thermal noise” are shown in Fig. 4(a) and (b), respectively. The thermal noise is a broadband noise, while the light emitted from fluorescent source has a dominant tone at 90 kHz and a harmonic tone at 180 kHz. All gas discharge lamps, including the fluorescent lamps, require a ballast to operate. The ballast offers a high initial voltage to start the gas discharge process. Also, the ballast converts the 60-Hz main supply frequency to high frequency to operate the fluorescent lamps more efficiently. The conventional fluorescent lamp is usually operated in the kilohertz range. As the spectrum of the Manchester-coded signal does not have the frequency components at low frequency; thus, it can significantly mitigate the background fluorescent noise effectively.

Then, we analyze the principle of Manchester coding to mitigate the optical background noise. In the decoding of Manchester signal as shown in Fig. 1, the received signal will minus its half-bit delay waveform. The decoding is represented as a transfer function $h(t)$

$$h(t) = \delta(t) - \delta(t - \tau) \tag{2}$$

where T is the half-bit delay time in the decoding process. The Fourier transform of $h(t)$ can be expressed as $H(f)$

$$H(f) = 1 - \exp^{-j2\pi f \tau}. \tag{3}$$

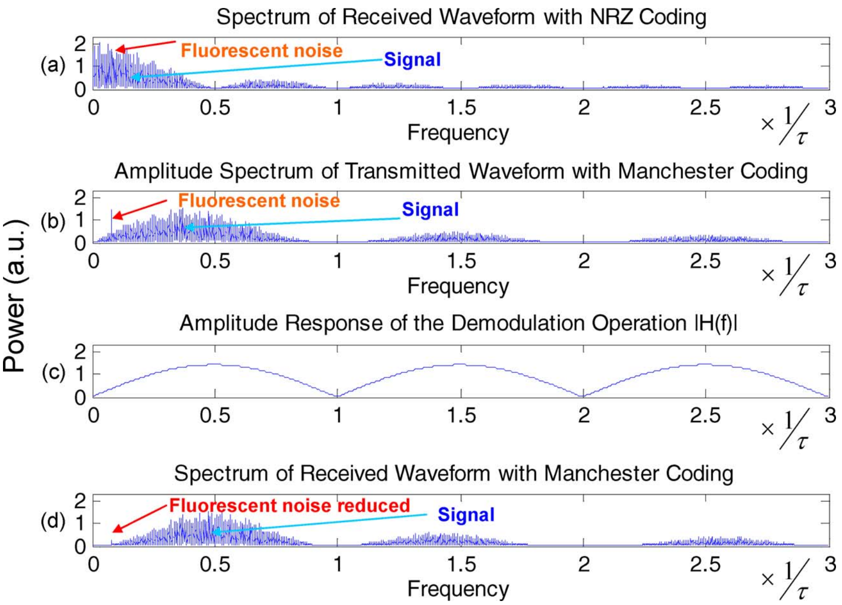


Fig. 5. Simulated power spectra of the (a) received NRZ signal, (b) received Manchester signal, (c) transfer function of decoding process, and (d) decoded Manchester signal.

The power of the transfer function is given as

$$\begin{aligned} |H(f)| &= |1 - \exp^{-j2\pi f\tau}| = |(1-\cos(2\pi f\tau)) - j\sin(2\pi f\tau)|^2 \\ &= \left((1-\cos(2\pi f\tau))^2 + \sin^2(2\pi f\tau)\right)^{\frac{1}{2}} = (2(1-\cos(2\pi f\tau)))^{\frac{1}{2}}. \end{aligned} \tag{4}$$

We can observed the transfer function in (4) is equal to zero at DC (when frequency $f = 0$) and is maximum when $f = 1/2T$. Fig. 5 shows the simulation results to explain the noise mitigation principle of the Manchester signal. Fig. 5(a) and (b) shows the power spectra of the NRZ coding and Manchester coding, both with the optical noise at frequency of $0.08/T$. Due to the high spectral overlap of the optical noise with the power spectrum of the NRZ signal, strong signal distortion is observed in NRZ case. In the Manchester decoding, the received signal [see Fig. 5(b)] will go through the decoding process, which is equivalent to passing through a periodic bandpass filter, as shown in Fig. 5(c) [derived in (4)]. Hence, the optical noise can be effectively filtered, as shown in Fig. 5(d). When the data rate of the Manchester signal is increased, its power spectrum will shift to higher frequency [see Fig. 5(b)]. The signal spectrum is frequency shifted away from the optical noise, assuming the frequency of the optical noise is fixed. Hence, the optical noise mitigation can be improved.

Further experiments were carried out to evaluate the performance of Manchester-coded optical wireless communication signal. Here, we used another white-light LED electrically driven by different modulation frequencies to emulate the background noises generated by AC-LEDs operated at different frequencies. The experimental setup was similar to that shown in Fig. 2. In this evaluation, the noise optical power was equal to the signal optical power. Both Manchester- and NRZ-coded signals were operated at 1.25 Mb/s. Fig. 6(a) shows the BER of the Manchester- and NRZ-coded optical wireless communication signals under different frequencies of the optical noise. Manchester signal performs better than the NRZ signal when the noise frequencies are below 500 kHz. This can be explained using (4). For example, when the frequency of the interference is at $f = 0$ (DC), the response of (4) is zero, which has an effect of attenuating the noise perfectly. This is the stopband for noise. When $f = 1/2T$ (1.25 MHz in this case), the function reaches a maximum value, and it is a passband for noise. Hence, the Manchester-coded signal has significant signal improvement when the noise is at and near the stopband of (4), and the signal improvement is decreased when

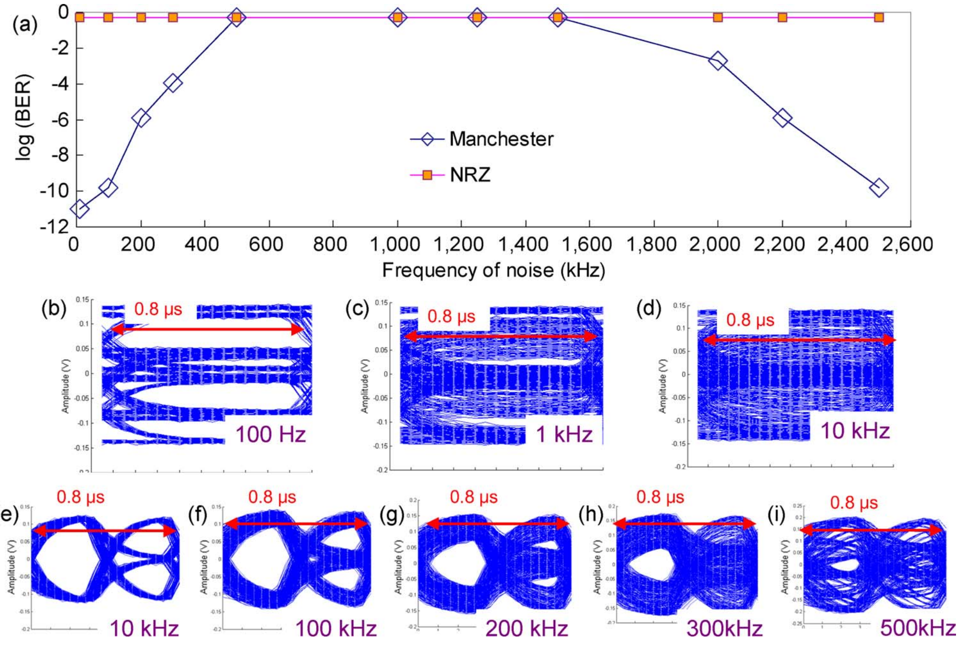


Fig. 6. (a) *BER* of NRZ- and Manchester-coded optical wireless communication signals at 1.25 Mb/s under different frequencies of the background noise. Insets: (b)–(d) Measured 1.25 Mb/s eye diagrams of NRZ optical wireless communication signals when subjected to different noise frequencies. (e)–(i) Measured 1.25 Mb/s eye diagrams of Manchester-coded signals when subjected to different noise frequencies.

the noise is approaching the passband of (4). Fig. 6(b)–(i) shows the corresponding measured 1.25 Mb/s eye diagrams of NRZ- and Manchester-coded signals subjected to different optical noise frequencies, respectively. We can see clearly that the NRZ signal is significantly degraded by the background noise even at now frequency of 100 Hz. For the Manchester-coded signal, although the eye diagram starts to degrade at 200 kHz, error-free transmission $(\mathrm{BER} < 1 \times 10^{-9})$ can be achieved.

5. Conclusion

We have successfully demonstrated using Manchester coding for the LED to mitigate the optical background noises. The Manchester coding has significant effect for signal quality improvement under the interference in particular frequency bands. The Manchester coding is also a line code that provides synchronization, so it is advantageous to use it in communications. Besides the Manchester coding, other forward error correction (FEC) techniques can also be used as the second layer of coding to further enhance the transmission performance. In this experiment, no adaptive monitoring, feedback, or optical filtering was required. At the bit rate of 1.25 Mb/s, the BER of Manchester-coded optical wireless communication was error-free $(Q > 14)$ in all the measurements, while the transmission of the NRZ-coded optical wireless communication produced error even at low F/T of 10 dB. When the F/T increases to 40 dB, the BER of the NRZ-coded optical wireless communication is only 1.5×10^{-3}. At the bit rate of 2.5 Mb/s (in this case, we over modulated the LED light), hence, the Q-factors of both Manchester- and NRZ-coded signals decreased due to the ISI generated by the limited modulation bandwidth. However, we have observed that Manchester-coded signal performed better since the differential decoding of the Manchester signal can reduce the ISI and enhance the eye opening of the received signal. Hence, error-free operation can be achieved even the LED was over modulated by about 2.5 times. The theoretical and numerical analysis of Manchester decoding process to mitigate the optical background noise has been provided. Further experiments have carried out to evaluate the performance of

Manchester-coded optical wireless communication signal using different optical noise frequencies generated by AC-LEDs, and the experiment results showed that Manchester coding performed better than the conventional NRZ when the noise frequency was $<$ 500 kHz.

References

[1] X. Zhang, B. Hraimel, and K. Wu, “Breakthroughs in optical wireless broadband access networks (Invited paper),” *IEEE Photon. J.*, vol. 3, no. 2, pp. 331–336, Apr. 2011.

[2] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, “Impact of crosstalk on indoor WDM optical wireless communication systems,” *IEEE Photon. J.*, vol. 4, no. 2, pp. 375–386, Apr. 2012.

[3] C. W. Chow, C. H. Yeh, Y. Liu, and Y. F. Liu, “Digital signal processing for light emitting diode based visible light communication (Invited paper),” *Proc. IEEE Photon. Soc. Newslett., Res. Highlights*, pp. 9–13, Oct. 2012.

[4] Z. Wang, C. Yu, W.-D. Zhong, J. Chen, and W. Chen, “Performance of a novel LED lamp arrangement to reduce SNR fluctuation for multi-user visible light communication systems,” *Opt. Exp.*, vol. 20, no. 4, pp. 4564–4573, Feb. 2012.

[5] W.-Y. Lin, C.-Y. Chen, H. H. Lu, C.-H. Chang, Y.-P. Lin, H.-C. Lin, and H.-W. Wu, “10m/500 Mbps WDM visible light communication systems,” *Opt. Exp.*, vol. 20, no. 9, pp. 9919–9924, Apr. 2012.

[6] C. W. Chow, C. H. Yeh, Y. F. Liu, and Y. Liu, “Improved modulation speed of the LED visible light communication system integrated to the main electricity network,” *Electron. Lett.*, vol. 47, no. 15, pp. 867–868, Jul. 2011.

[7] C. H. Yeh, Y. F. Liu, C. W. Chow, Y. Liu, P. Y. Huang, and H. K. Tsang, “Investigation of 4-ASK modulation with digital filtering to increase 20 times of direct modulation speed of white-light LED visible light communication system,” *Opt. Exp.*, vol. 20, no. 15, pp. 16 218–16 223, Jul. 2012.

[8] D. Lee, K. Choi, K.-D. Kim, and Y. Park, “Visible light wireless communications based on predistorted OFDM,” *Opt. Commun.*, vol. 285, no. 7, pp. 1767–1770, Apr. 2012.

[9] V. G. Yánez, J. R. Torres, J. B. Alonso, J. A. R. Borges, C. Q. Sánchez, C. T. González, R. P. Jiménez, and F. D. Rajo, “Illumination interference reduction system for VLC Communications,” in *Proc. WSEAS Int. Conf. Math. Methods, Comput. Tech. Intell. Syst.*, 2009, pp. 252–257.

[10] S.-H. Yang, H.-S. Kim, Y.-H. Son, and S.-K. Han, “Reduction of optical interference by wavelength filtering in RGB-LED based indoor VLC system,” in *Proc. OECC*, 2011, pp. 551–552.

[11] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using LED lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.

[12] G. P. Agrawal, *Fiber-Optic Communication Systems*. New York: Wiley, 2010.