An Indicator-Based Visible Light Communication System Embedding on Operating Systems: Signal Design and Experimental Verification

Xinchi Rong, Chao Wang, Jiawei Ren and Yijun Zhu*
Information Engineering University, Zhengzhou, Henan Province (450000), China.

*Corresponding author. Email: vijunzhu@outlook.com

Abstract. Light emitting diode(LED) sources are massively distributed in the computers, display screens and other industrial electronics terminal devices, which not only indicate device status, but can also be used for information transmission. This paper takes a hard drive disk LED indicator embedded on a personal computer as example for statistical analysis. However, due to the fact that we cannot skip the operating system to control the indicators directly, the problem of clock drift is particularly serious. In response, we put forward our scheme of pulse width long-short-key modulation instead of traditional on-off-keying (OOK) modulation, which is optimized by simulation and verified by hardware experiment subsequently. As is indicated in the experiment, our modulation is superior to traditional OOK scheme at the same average data rate. Based on the analysis above, programming interfaces of sending and receiving terminals are designed to transmit real-time messages, files, or voice signal.

Keywords: Light Emitting Diode (LED), Visible Light Communication(VLC), clock drift, single photon avalanche diode, pulse width long-short-key modulation.

1. Introduction
With the advantages of wide spectrum, high security and environmental friendliness, VLC systems can be utilized in indoor high-speed wireless communication, indoor navigation, indoor positioning and so on [1]-[4].

In fact, besides normal LED lamps used in indoor lighting, a large number of LED sources are distributed in the computers, mobile phones, display screens and other electronic terminal devices. In addition to indicating the current state, these LED indicators could also be utilized creatively as the transmitter of some typical VLC systems[5],[6]. Three advantages of this work can be easily listed. Firstly, the hard drive disk (HDD) LED indicators are ubiquitous in most network devices, which makes our research worth popularizing. Secondly, no extra hardware overhead is needed in the system, which makes it simple to install and convenient for the use. Thirdly, it supply a new way for information exchange, which can not only become a vital substitute for cable and RF transmission method, but also cater to the developing trend of the ‘Internet of everything’, which is the core idea of the coming 6G.

In [7], a liquid crystal display screen, which can also be regarded as a kind of LED indicators, is served as a transmitter. In [8], the keyboard is used to send data optically. Monitor's indicators are used
in [9]. And hard drive LEDs are also served in [10]. In [11], binary frequency shift keying (B-FSK) is used instead of OOK in modulation. A row of router status LEDs are used simultaneously and some modulation schemes are presented in [12]. Nevertheless, there is no systematic analysis to the signal model in this scenario from the perspective of communication science. The receiver presented in the above-mentioned papers is always cameras or other simple optical sensors, which is unable to meet the demand of high-speed transmission and weak illumination. Hence, a single photon avalanche diode (SPAD) device which has already been widely used for photon counting is attempted to be applied as a receiver. A statistical modeling of SPAD receivers is given in [13].

Aim at these problems herein-before, an experimental system with a practical HDD status indicator and an SPAD detector is built in this paper. On the prerequisite of no damage to the existing hardware, a malicious software needs implanting to its hard disk for indirect control. An obvious problem of clock drift emerges, for no precise clock is available for an embedded software. As a result, we put forward an effective modulation scheme of pulse width long-short-keying (PWLSK) modulation. We optimize the design of parameters based on the previously obtained signal model parameters and give the general criteria for the selection of modulation parameters. Finally, we verify the correctness of signal model and the superiority of our scheme. At the same average bit rate, the optimized modulation scheme can gain a lower bit error rate (BER) performance.

2. Experimental System Setup and Signal Model Analysis

2.1. Signal Scheme of Pulse Width Long-Short-Key Modulation

![Figure 1. Experimental system of SPAD-VLC with an HDD indicator.](image)

The experimental setup of the HDD indicator system is shown in Fig. 1. In this system, an HDD indicator controlled by a previously designed program embedded into the OS (operating system, Windows XP) of an PC (personal computer, Lenovo) is served as transmitter. The HDD indicator in the system is a common LED indicator with the power of around 10 mW. The SPAD receiver is 10 meters away from the HDD LED and the ambient light intensity is no more than 20lx. In order to collect the weak signal better and extend the available communication distance as much as possible, a customized
optical receiving system with convergent lens is used in the receiver front-end and a commercial SPAD (Excelitas Technologies, SPCM-AQRH-15-FC) is utilized to receive the optical signals as well. Both the signal and ambient light go into the SPAD before converted to electrical signal, which is connected to an oscilloscope (Agilent, DSO9064A) for a clearer observation.

2.2. Statistical signal model of the embedded indicator system

We could only carry on specific hard disk operations of ‘read’ or ‘write’ to indirectly manipulate the indicator to generate the signal without breaking the infrastructure of a PC. Actually, when the PC reads different sizes of data blocks, the time it takes obviously differs. The statistical result is shown in Table 1.

| size of data block | mean of ‘1’[μs] | standard deviations(SD) of ‘1’ | mean of ‘0’[μs] | SD of ‘0’ |
|-------------------|-----------------|--------------------------------|-----------------|----------|
| 1Kb               | 22.26           | 0.984221492                   | 45.00           | 42.33657744 |
| 2Kb               | 25.69           | 0.852138999                   | 49.87           | 40.03812071 |
| 4Kb               | 29.02           | 6.213707153                  | 151.01          | 2258.048822 |
| 8Kb               | 43.59           | 67.85557004                  | 167.75          | 1168.552572 |
| 16Kb              | 72.94           | 84.78317837                  | 233.91          | 1194.710891 |
| 32Kb              | 132.97          | 207.8351951                  | 405.52          | 2771.963648 |
| 64Kb              | 252.56          | 366.1164998                  | 526.45          | 2261.053386 |
| 128Kb             | 485.37          | 413.0350958                  | 903.53          | 11129.03364 |
| 256Kb             | 1194.79         | 1626.902795                  | 1849.08         | 46500.68508 |
| 512Kb             | 2522.98         | 6129.047489                  | 3319.68         | 78416.14707 |

3. Signal design and theoretical analysis

In this paper, we differ the size of data blocks to indirectly control the duration of LED-ON. Fig. 2(a) shows the main point of our modulation scheme. Firstly, two different particular sizes of data block will be selected. When we need to transmit bit ‘1’, the program will order the HDD to read the bigger data block once, which takes the time of \( t_1 \). The HDD will then wait for the time of \( t_2 \) until the next bit comes. Similarly, the program will order the HDD to read the smaller data block once, when we need to transmit bit ‘0’, which takes the time of \( t_3 \), and wait for the time of \( t_4 \).

![Figure 2. Mathematical model and actual waveform of PWLSK.](image)

Using the mathematical modeling presented in [13], we can get the BER performance of each data size group. Based on this, a two-dimensional coordinate with x-axis of BER and y-axis of average bit rate is established. Each points at height given with the value of every scheme is plotted in Fig. 3(a). As for PWLSK, the greater the difference between two selected data block, the lower the BER performance. Take the data rate into account, the smaller size of data block should be as small as possible. When the smaller data block size is 1Kb, it always has the highest data rate with same BER performance and
lowest BER with same data rate. Therefore, we connect these points and get the optimized data block size selection scheme of PWLSK. If we limit the BER not less than $10^{-4}$, choosing 1Kb and 16Kb size is the optimal scheme. If we limit the BER not less than $10^{-8}$, 1Kb and 32Kb size is the optimal scheme.

(a) Average data rate and BER of PWLSK (b) Comparison between OOK and PWLSK.

**Figure 3.** Experimental BER analysis of PWLSK.

In order for comparison, the characters of scheme OOK modulation with different data block size are also plotted in Fig. 3(b). Although OOK modulation has the lower BER when average data rate is more than 7Kbps, it never decline the BER to less than $10^{-4}$, which is unable to meet communication demand.

4. Experimental verification

In this section, experimental system shown in Fig. 1 is set up again to furtherly verify our conclusion. This time we modulate the VLC signal with designed scheme of PWLSK.

(a) Sending terminal interface. (b) Sending terminal interface.

**Figure 4.** Our achievement exhibiting of terminal interface.

Finally, programming interface of both sending and receiving terminals are also be designed and shown in Fig. 4, which is able to carry real time message, file and voice signal services. 1Kb and 16Kb data block size is selected for ‘0’, ‘1’ bit transmission. Due to complexion and instability of channel and OS, extra overhead is needed coding and synchronization. The average data rate is 1.8kbps experimentally, which is lower than the simulation one.
5. Conclusion
In this paper, we take the embedded operating system with the LED light on the independent control as an example to discuss all potential VLC system with LED embedded on an OS. The clock drift and signal processing problems with SPAD served as receiver in weak light situation is overcome. Our scheme of PWLSK is given, which is verified superior to OOK. Selection principle of data block size when transmitting ‘0’, ‘1’ bit is analyzed. That is, the greater the difference of two data block size, the better. However, it is guaranteed that the data block sending ‘0’ is not too small to be submerged in ambient light.

Acknowledgement
The work of this paper is financially supported by the National Key Research and Development Project(2018YFB1801903) and the National Natural Science Foundation of China (NSFC) under Grant 61671477, 61901524.

References
[1] A. Jovicic, J. Li, T. Richardson, Visible light communication: opportunities, challenges and the path to market, IEEE Commun. Mag, vol. 51, no. 12(2013) pp. 26-32.
[2] Surve H. Visible Light Communication. International Journal for Research in Applied Science and Engineering Technology, vol. 7, no.4(2019) pp. 1820-1822.
[3] Luo J, Fan L, Li H, et al. Indoor Positioning Systems Based on Visible Light Communication: State of the Art. IEEE Communications Surveys and Tutorials, vol. 19, no. 4(2017) pp. 2871-2893.
[4] Cailean A, Dimian M. Current Challenges for Visible Light Communications Usage in Vehicle Applications: A Survey. IEEE Communications Surveys and Tutorials, vol. 19, no. 4(2017) pp. 2681-2703.
[5] D. Tsonev et al., A 3-Gb/s Single-LED OFDM-Based Wireless VLC Link Using a Gallium Nitride μLED, IEEE Photon. Technol. Lett., vol. 26, no. 7(2014) pp. 637-640.
[6] R. X. G. Ferreira et al., High Bandwidth GaN-Based Micro-LEDs for Multi-Gb/s Visible Light Communications, IEEE Photon. Technol. Lett., vol. 28, no. 19(2016) pp. 2023-2026.
[7] M. Guri, Optical air-gap exfiltration attack via invisible images, Workshop on Information Security and Applications, vol.46(2019) pp.222-230.
[8] M. Guri, B. Zadov, D. Bykhovsky et al., CTRL-ALT-LED: Leaking Data from Air-Gapped Computers via Keyboard LEDs, 2019 IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC), Jul. 2019, pp. 801-810.
[9] M. Guri, B. Zadov, E. Atias, and Yuval Elovici, LED-it-GO: Leaking(a lot of) Data from Air-Gapped Computers via the (small) Hard Drive LED, International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment, Bonn Germany, Jul. 2017, pp. 161-184.
[10] V. Sepetnitsky, M. Guri, and Y. Elovici, Exfiltration of Information from Air-Gapped Machines Using Monitor's LED Indicator, 2014 IEEE Joint Intelligence and Security Informatics Conference, Sep. 2014, pp. 264-267.
[11] Z. Zhou, W.-M. Zhang, Z.-C. Yang, N.-H. Yu, Exfiltration of Data from Air-gapped Networks via Unmodulated LED Status Indicators, arXiv: Cryptography and Security, 2017.
[12] M. Guri, B. Zadov, D. Bykhovsky, and Y. Elovici, xLED: Covert Data Exfiltration from Air-Gapped Networks via Router LEDs, arXiv: Cryptography and Security, 2017.
[13] E. Sarbazi, M. Safari, and H. Haas, Statistical Modeling of Single-Photon Avalanche Diode Receivers for Optical Wireless Communications, IEEE Trans. Commun., vol. 66, no. 9(2018) pp. 4043-4058.